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Sustainability through MuSIASEM nexus analysis: the case of Andorra

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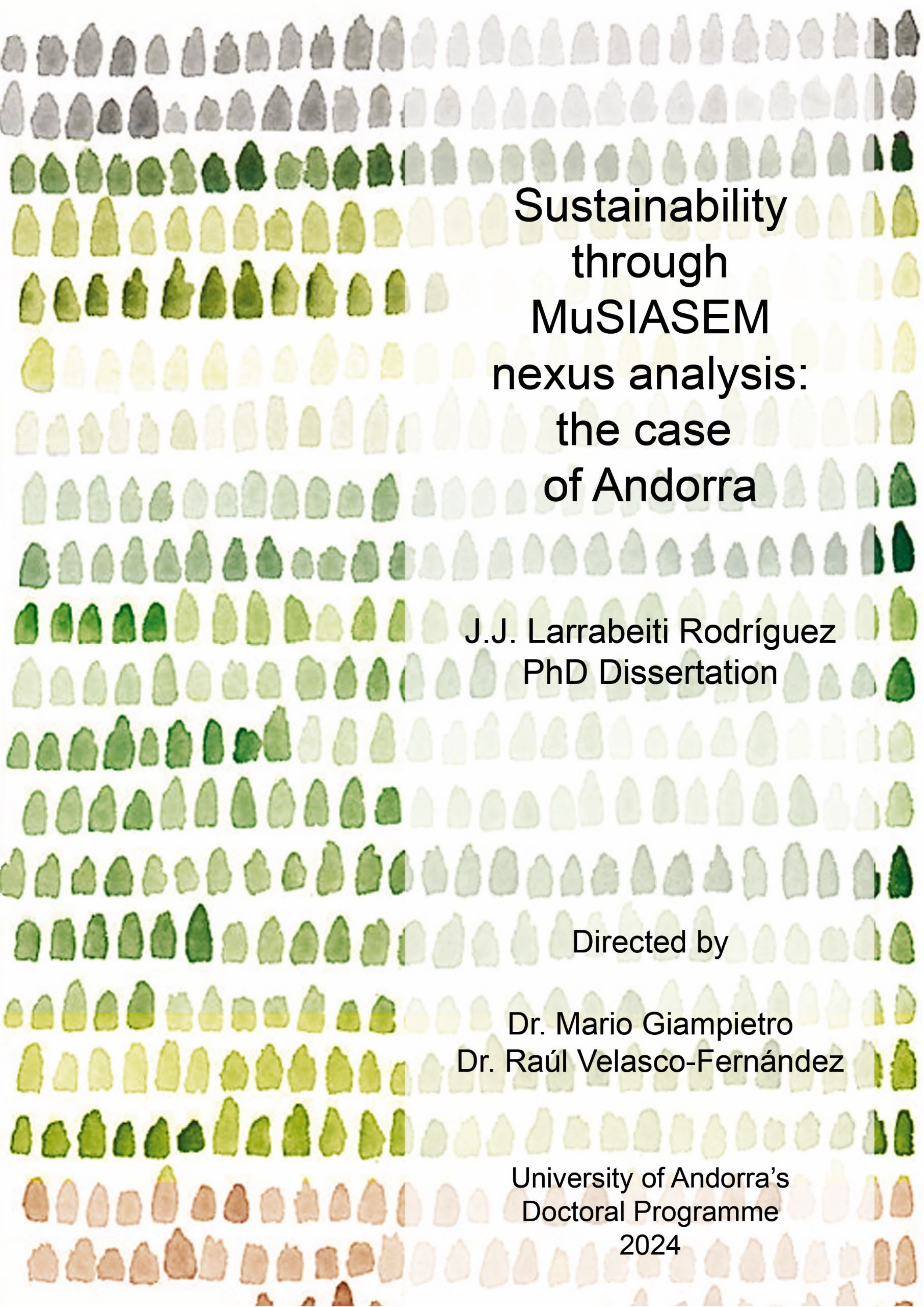

Sustainability through MuSIASEM nexus analysis: the case of Andorra

J.J. Larrabeiti Rodríguez
PhD Dissertation

Directed by

Dr. Mario Giampietro
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University of Andorra's
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2024

Sustainability through MuSIASEM nexus analysis: the case of Andorra

La sostenibilitat a través de l’anàlisi nexe MuSIASEM: el cas d’Andorra

J.J. Larrabeiti Rodríguez

PhD dissertation for the University of Andorra’s Doctoral Programme

Directed by

Dr. Mario Giampietro | Dr. Raúl Velasco-Fernández

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Covers and metaBols: Eve Ariza.

En señal de admiración por su genio,

dedico este trabajo a Anna, Nathaniel y Valentina.

Table of contents

List of Figures

List of Tables

Acronyms

General

CE	Conventional economics
CN	Combined nomenclature
EE	Ecological economics
EROI	Energy Returned on Energy Invested
EU	European Union
EVs	Electric vehicles
GDP	Gross domestic product
GHG	Greenhouse gas
LCA	Life Cycle Analysis
MEFA	Material and Energy Flow Analysis
MRIO	Multi-Regional Input-Output
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
PES	Primary energy sources
QST	Quantitative Storytelling
SES	Social-ecological system
SMR	Sociometabolic research
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet

Compartments of socio-ecological systems

AG	Agricultural sector
HH	Household sector
ICM	Industry, construction and manufacturing sector
PW	Paid work sector
SG	Service and government sector

MuSIASEM analytical tools and attributes

E	Electricity
ELP	Economic labour productivity
ELUP	Economic land use productivity
EMD	Exosomatic metabolic density
EMR	Exosomatic metabolic rate
EPM	Environmental pressure matrix
EUM	End-use matrix
F	Fuel
GER	Gross energy requirement
GVA	Gross value added
H	Heat
HA	Human activity
LU	Land use
NML	Non-managed land
SW	Solid waste
WMD	Water metabolic density
WMR	Water metabolic rate
WT	Water throughput

Units

GJ	Gigajoule
GWh	Gigawatts hour
h	Hour
ha	Hectare
l	Litre
MJ	Megajoule
p.c.	per capita
T.E.	Thermal equivalent
tCO_2eq	Tonnes CO_2 equivalent
TJ	Terajoule

Abstract

This thesis insists that the polycrisis affecting human societies —consisting of biodiversity loss, land degradation, climate change, and waste production, among others— is rooted in a “crisis of perception”. The preset prevalence of the narratives proposed by conventional economics has produced a distorted worldview where social and economic structures’ dependence on a biophysical reality is systematically ignored or, at best, minimised. Intending to transform our existing perceptions and representations of society-nature interactions into a more holistic one that accounts for different biophysical limits, this thesis builds on the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). This methodological approach tackles the complexity associated with the generation of quantitative models of sustainability issues by integrating different dimensions of analysis (e.g. economic, demographic and biophysical), different scales (i.e. the whole, its compartments and the relation between the whole and other systems) and information referring to non-equivalent descriptive domains (e.g. use of secondary inputs like energy carriers and primary sources like oil or water).

The thesis is developed at two levels: methodologically and analytically. Methodologically, I critically appraise conventional economics when studying sustainability problems (Chapter 2). Subsequently, I discuss the appropriateness of MuSIASEM to address these issues, delving into its theoretical foundations and offering a detailed overview of the analytical tools available within the approach for addressing various relevant aspects concerning the sustainability of social-ecological systems. Lastly, I mention some practical examples where MuSIASEM has been applied and clarify some problems that arise when using such a protocol (Chapter 3).

Analytically, I apply a set of epistemological tools developed in the latest version of MuSIASEM to the Andorra case study, aiming to provide a comprehensive understanding of its sustainability. This analytical endeavour serves a dual purpose: (i) generating valuable descriptions by considering Andorra a social-ecological system, which involves performing a biophysical analysis, characterising the metabolic pattern of Andorra (Chapter 4) and an externalisation analysis, accounting for the nexus elements embodied in energy and food imports (Chapter 5); and (ii) analysing the framing of the country’s sustainability policy, with a focus on the existing narratives (Chapter 6). The choice of Andorra as a case study is not merely incidental. With its unique blend of urban and rural characteristics and relative simplicity, this region serves as an ideal case study within Europe. It offers a practical guide for applying all MuSIASEM assessment tools and for developing integrated sociometabolic analyses in larger countries.

In summary, the primary goal of this thesis is to articulate a sound sustainability analysis that provides valuable and alternative representations on the scientific side, offering possibilities for fairer ecological futures where environmental sustainability and well-being are central axes.

Keywords: Andorra, Ecological Economics, Externalisation, Integrated Analysis, MuSIASEM, Nexus Analysis, Sociometabolic Research, Societal Metabolism, Socio-Ecological Systems, Sustainability.

Resum

Aquesta tesi insisteix que la crisi múltiple que afecta les societats humanes —consistent en la pèrdua de biodiversitat, la degradació de la terra, el canvi climàtic i la producció de residus, entre altres elements— té la seva arrel en una “crisi de percepció”. L’actual prevalença de les narratives proposades per l’economia convencional ha generat una visió del món distorsionada on la dependència de les estructures socials i econòmiques d'una realitat biofísica és sistemàticament ignorada, o, en el millor dels casos, minimitzada. Amb la intenció de transformar la nostra actual percepció i representació de les interaccions societat-naturalesa en una més holística que tingui en compte l'existència de diferents límits biofísics, aquesta tesi es basa en l’Anàlisi Integrada Multiescalar del Metabolisme Social i Ecosistèmic (MuSIASEM de les seves sigles en anglès). Aquest enfocament metodològic aborda la complexitat associada a la generació de models quantitatius sobre qüestions de sostenibilitat, integrant diferents dimensions d’anàlisis (p. ex. econòmica, demogràfica i biofísica), diferents escales (això és, el total, els seus compartiments i les relacions entre el total i altres sistemes), i informació relativa a dominis descriptius no equivalents (p. ex. l’ús d’inputs secundaris com els productes energètics i fonts primàries com el petroli o l’aigua).

La tesi es desenvolupa en dos nivells: metodològic i analític. En l’àmbit metodològic, avaluo críticament l’economia convencional quan estudia problemes de sostenibilitat (Capítol 2). Posteriorment, discuteixo la conveniència de MuSIASEM per a abordar aquestes qüestions, submergint-me en els seus fonaments teòrics i oferint una visió detallada de les eines analítiques disponibles dins de l'enfocament per a abordar diversos aspectes rellevants relatius a la sostenibilitat dels sistemes socioecològics. Finalment, comento alguns exemples pràctics on la metodologia s’ha aplicat i aclareixo alguns problemes que sorgeixen a l'hora d'utilitzar un protocol d’aquest tipus (Capítol 3).

En l’àmbit analític, aplico un conjunt d'eines epistemològiques desenvolupades en l'última versió de MuSIASEM al cas d'estudi d’Andorra amb el propòsit de proveir amb una comprensió integral de la seva sostenibilitat. Aquest esforç analític té un doble objectiu: (i) generar descripcions valuoses, considerant Andorra com un sistema socioecològic, duent a terme una anàlisi biofísica per a caracteritzar el patró metabòlic d’Andorra (Capítol 4) i una anàlisi d'externalització que comptabilitza els elements nexe incorporats en les importacions d'energia i aliments (Capítol 5); i (ii) analitzar el marc de les polítiques de sostenibilitat del país amb un èmfasi en les narratives existents (Capítol 6). L'elecció d'Andorra com a cas d'estudi no és merament accidental. Amb la seva mescla única de característiques urbanes i rurals i relativa simplicitat, aquesta regió és un estudi de cas ideal dins d’Europa. Ofereix una guia pràctica per a l'aplicació de totes les eines d'avaluació de MuSIASEM i per al desenvolupament d'anàlisis sociometabòliques integrades en països més grans.

En resum, l'objectiu principal d'aquesta tesi és articular una anàlisi de sostenibilitat sòlida que proporcioni representacions valuoses i alternatives en el vessant científic, oferint possibilitats per a futurs ecològics més justos on la sostenibilitat i el benestar siguin eixos centrals.

Paraules clau: Andorra, Economia Ecològica, Externalització, Anàlisi Integrada, MuSIASEM, Anàlisi Nexe, Recerca Sociometabòlica, Metabolisme Social, Sistemes Soci-Ecològics, Sostenibilitat.

Resumen

Esta tesis insiste en que la crisis múltiple que afecta a las sociedades humanas —consistente en la pérdida de biodiversidad, la degradación de la tierra, el cambio climático y la producción de residuos, entre otros elementos— tiene su raíz en una "crisis de percepción". La actual prevalencia de las narrativas propuestas por la economía convencional ha generado una visión del mundo distorsionada en donde la dependencia de las estructuras sociales y económicas de una realidad biofísica es sistemáticamente ignorada, o, en el mejor de los casos, minimizada. Con la intención de transformar nuestra actual percepción y representación de las interacciones sociedad-naturaleza en una más holística que tenga en cuenta la existencia de diferentes límites biofísicos, esta tesis se basa en el Análisis Integrado Multiescalar del Metabolismo Societal y Ecosistémico (MuSIASEM de sus siglas en inglés). Este enfoque metodológico aborda la complejidad asociada a la generación de modelos cuantitativos sobre cuestiones de sostenibilidad, integrando diferentes dimensiones de análisis (p. ej. económica, demográfica y biofísica), diferentes escalas (esto es, el total, sus compartimentos y las relaciones entre el total y otros sistemas), e información relativa a dominios descriptivos no equivalentes (p. ej. el uso de inputs secundarios como los productos energéticos y fuentes primarias como el petróleo o el agua).

La tesis se desarrolla en dos niveles: metodológico y analítico. A nivel metodológico, evalúo críticamente la economía convencional cuando estudia problemas de sostenibilidad (Capítulo 2). Posteriormente, discuto la conveniencia de MuSIASEM para abordar estas cuestiones, sumergiéndome en sus fundamentos teóricos y ofreciendo una visión detallada de las herramientas analíticas disponibles dentro del enfoque para abordar diversos aspectos relevantes relativos a la sostenibilidad de los sistemas socio-ecológicos. Por último, comento algunos ejemplos prácticos en donde la metodología se ha aplicado y aclaro algunos problemas que surgen a la hora de utilizar un protocolo de este tipo (Capítulo 3).

A nivel analítico, aplico un conjunto de herramientas epistemológicas desarrolladas en la última versión de MuSIASEM al caso de estudio de Andorra con el propósito de proveer con una comprensión integral de su sostenibilidad. Este esfuerzo analítico tiene un doble objetivo: (i) generar descripciones valiosas, considerando Andorra como un sistema socio-ecológico, realizando un análisis biofísico para caracterizar el patrón metabólico de Andorra (Capítulo 4) y un análisis de externalización que contabiliza los elementos nexo incorporados en las importaciones de energía y alimentos (Capítulo 5); y (ii) analizar el marco de las políticas de sostenibilidad del país con un énfasis en las narrativas existentes (Capítulo 6). La elección de Andorra como caso de estudio no es meramente accidental. Con su mezcla única de características urbanas y rurales y su relativa simplicidad, esta región es un estudio de caso ideal dentro de Europa. Ofrece una guía práctica para la aplicación de todas las herramientas de evaluación de MuSIASEM y para el desarrollo de análisis sociometabólicos integrados en países más grandes.

En resumen, el objetivo principal de esta tesis es articular un análisis de sostenibilidad sólido que proporcione representaciones valiosas y alternativas en el lado científico, ofreciendo posibilidades para futuros ecológicos más justos en donde la sostenibilidad y el bienestar sean ejes centrales.

Palabras clave: Andorra, Economía Ecológica, Externalización, Análisis Integrado, MuSIASEM, Análisis Nexo, Investigación Sociometabólica, Metabolismo Social, Sistemas Socio-Ecológicos, Sostenibilidad.

Preface

> "Hay algunas empresas en las cuales
> un cuidadoso desorden
> es el mejor método".
> Herman Melville[*].

Motivation

This work is the result of a long process which began several decades ago while attending my studies in economics at the University of Alicante in the 1990s. The primary motivation for this thesis is a profound dissatisfaction with the traditional role assigned to an economist. I firmly believe that economics should be more holistic and systemic, studying how human systems organise the flows of goods and services necessary for survival and reproduction under various institutional arrangements. The main economic problem, therefore, is social provisioning, which requires understanding the constraints imposed by the biophysical reality in which human structures operate. However, the economics I studied, still taught in standard courses, is focused on achieving equilibrium allocations within the narrow confines of self-regulated markets.

The vision of conventional economics generated deep internal dissonances in me. First, most things that matter to people and affect corporate profits are not traded in the markets. Thus, we can think of the impossibility of putting a price on and commercialising birds singing at the beginning of spring, the possibility of life linked to the water cycle, or the attentive care of parents for their children. Secondly, with its fetishism of merchandise and money, the conventional economics view makes us insensitive to the deep interdependencies between humans and eco dependencies with nature, perpetuating an unsustainable lifestyle that should be more humble, sensitive, and open to the processes of nature that sustain us and to the relational and complex character of human ties.

A rudder turn nullified this background noise in my insides. After finishing my studies and working for a few months in the banking sector, I moved to Barcelona to dedicate myself to something that could capture the beauty and unquantifiable nature of existence: audiovisual production. For over a decade, I worked for different film

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[*] Extract from *Moby Dick*, whose original version dates to 1851. Melville, H. (2011). Moby Dick. Edición ilustrada por Rockwell Kent. Valdemar, Madrid, p. 545.

production companies in some quite wild, romantic, and, seen from a distance, somewhat empty-headed years.

The profound economic and social crisis of 2008 renewed my interest in economics. Economic and social justice issues are inevitably linked to ecological considerations. The severe social effects associated with maintaining the current economic system that became evident during the crisis, the impossibility of exponential growth on a finite planet as a solution to these problems, and the need to provide dignified lives for the entire human population challenged me to confront the thorny plot of what is ecologically feasible and socially viable. Therefore, after a few months of reflection, I resumed my academic career by enrolling in an environmental and ecological economics distance course taught by Professor Walter Pengue.

After several years away from formal education, this online course was highly beneficial for synthesising conventional economics' approach to environmental issues. It also emphasises the limitations associated with traditional economics' obsession with monetary valuations and the need to overcome them through more holistic and multidimensional approaches. These latter approaches came from ecological economics... and I needed to know more.

Professor Pengue's recommendation letter, among other merits, was favourable for the acceptance into the Master of Environmental Studies at the Institute of Science and Technology (ICTA) in September 2011. The city of Barcelona, and especially the ICTA, has long become a reference point for the study of ecological economics at the global level. Therefore, during the master's degree, I was privileged to receive classes from influential scholars in ecological economics and related disciplines, such as environmental history. Professors like Joan Martinez-Alier, Erik Gomez-Baggethun, and Marco Armiero introduced me to influential authors like Karl Polanyi, Nicolas Georgescu-Roegen, and Marshall Sahlins, often overlooked by conventional economics. This training resulted in writing a master's thesis on water consumption in Alicante and the subsequent publication of the same as an article in the journal *Investigaciones Geográficas*.

After completing the master's degree, the logical next step was to pursue a doctorate. However, essential family issues related to the move to Andorra and the work of care associated with raising children postponed this stage. In any case, the germ of ecological economics had taken hold in me. Thanks to regular readings and contact with fellow masters, I continued to be linked to the discipline.

The possibility of pursuing a doctorate was reactivated in 2017 when I learned that I met the requirements to opt for the grants for the completion of third-cycle studies promoted by the *Departament d'Ensenyament Superior, Recerca i Ajuts a l'Estudi del Govern d'Andorra.* With the help of Raúl Velasco, a former master's classmate already finishing his doctorate, we prepared a dossier with an extremely short deadline that I did not defend well in front of the tribunal that granted the scholarship. Unfortunately, I did not get it. However, we did not give up. With more time and dedication, I got the scholarship in the next year's call. Therefore, I could start the doctorate with the tutoring of Raúl and Professor Mario Giampietro, a true eminence in the field of social metabolism with which Raul worked, who, with his immense sympathy, agreed to co-direct the thesis.

Here began a fundamental process of epistemological breakdown in the field of economics, which I always relate to what the main character of the film *They Live* (1988), directed by John Carpenter, was supposed to feel when he found the special glasses that made him see the world without veils, acknowledging the existence of an alien invasion. Thus, where supply and demand curves were previously present, there were now impredicative relationships between different functional and structural components. Where there were previously monetary valuations, complex relationships now appeared that could not be reduced to money. Instead of economic growth "*ad infinitum*", the economic process was now aimed at maintaining and reproducing society, constrained by limits of a different nature. Moreover, all of this was not just mental rambling but could be applied to where I lived and improve the quality of the debate on sustainability issues.

The result of this long journey is this thesis, which you are reading. It also represents the author's intellectual and ethical-moral transformation, which you cannot see, but I hope you can apprehend from its pages. In this way, I am at peace with myself and, to some extent, with what you should expect from an economist.

Acknowledgements

Ya que como la mayoría de las personas a las que quiero mostrar mis agradecimientos entienden el castellano, y es la lengua de mi intimidad, voy a escribir estos párrafos de agradecimiento en la llamada lengua de Cervantes.

Como el lector de esta tesis leerá en repetidas ocasiones, la base material sobre la que se asienta una sociedad impone restricciones a lo que es posible o deseable. En este sentido, sin ayuda financiera, me hubiese sido imposible realizar este trabajo de investigación. Así pues, estoy tremendamente agradecido a Helena Solé, del "Àrea de Recerca" del "Govern d'Andorra". Ella fue la que me animó a continuar cuando me denegaron la beca por primera vez y me alentó y aconsejó para postular una segunda vez. También hago extensivos los agradecimientos a Margarita Ceña, actual" Cap de l'Àrea de Recerca".

También quiero hacer públicos mis agradecimientos y respetos a toda la familia de Casa Colat del Pui de la Massana, y muy especialmente a Toni Ubach y Victorina Font. Ellos han sido los que me han tenido de "okupa" en Casa Colat, facilitándome un despacho, un entorno privilegiado, y todo tipo de comodidades con las que poder realizar este trabajo. Por los centenarios muros de la casa han pasado pensadores de la talla de Henri Lefebvre. Espero haber realizado una modesta contribución a la larga tradición intelectual de la casa.

Junto a los requerimientos materiales, también están los requerimientos de la razón. En este sentido, agradecer el trabajo y apoyo mostrado por los directores de esta tesis: Mario Giampietro y Raúl Velasco. Su entusiasmo por transgredir más allá del conocimiento establecido es contagioso. Pero lo mejor de ellos es que además de ser grandes investigadores, son mejores personas. Además, saben cuándo apretar, cuándo relajar y cuándo recogerte de entre los escombros del naufragio y darte aliento tras los momentos más difíciles.

A pesar de que escribir una tesis rodeado de las montañas de Andorra es un trabajo eminentemente solitario, la misma se ha nutrido de las ricas discusiones con otros miembros del "MuSIASEM team" en las ocasiones en que bajaba a Barcelona o con esporádicos contactos telemáticos. Así que me gustaría reconocer el apoyo de Ansel Renner, Juan José Cadillo, Miki Manfroni, Laura Pérez, Louisa Di Felice, Maddalena Rippa y Diana Alfonso. Especial mención merecen Sandra Bukkens por su estupendo trabajo de gestión y cuidados y Alejandro Marcos por su incondicional ayuda en diferentes etapas durante el trascurso de la tesis. También agradecer a Jon Apodaka, compañero de aventuras y desventuras del "Programa de Doctorat de la Universitat d'Andorra", los momentos de camaradería vividos. Asimismo, un agradecimiento especial merece Oriol Travesset, de "Andorra Recerca i Innovació", que me ha facilitado *ayuda constante tanto para temas de maquetación como para temas relacionados con los contenidos de la tesis en su aplicación a Andorra.*

En el plano emocional, me gustaría agradecer el apoyo de mis amigos de Alicante. Nunca han sabido muy bien qué hacía, pero ahí estaban ofreciendo un contrapunto necesario. Así pues, gracias Isaakito, Nachivirim, Beneytus, César y María. También dar las gracias a mi madre, Arantxa, de la que heredé el respeto por lo vivo y a mi hermana Arantxita.

Reconocer también el trabajo realizado por la artista andorrana Eve Ariza con la portada y la creación de los metaBols. Como gran artista que es, entendió enseguida el espíritu de "pensar en relación" que impregna la tesis a la vez que supo transgredir aquello que yo tenía pensado como portada y realizar algo propio.

Las montañas, prados, huertos y ríos de Andorra me han acompañado durante la escritura de este trabajo, y les estoy agradecido por la belleza que me han trasmitido. También a diversos lugares de los departamentos franceses de l'Ariège y l'Aude (con una mención especial al "Canal du Midi", obra que demuestra que el ingenio humano puede desplegarse con respeto al entorno natural).

Finalmente, este trabajo está dedicado a Anna Ubach, Nathaniel y Valentina Larrabeiti. Ellos hacen que luchar por un futuro mejor tenga pleno sentido.

Chapter 1

1. Introduction.

> "En ocasiones, un velo puede ser necesario,
> pero nunca una máscara".
> Nathaniel Hawthorne*.

1.1. Contextualisation.

The climate crisis continues to worsen after more than 60 years since the birth of modern environmentalism—with the publication of *Silent Spring* (Carson, 1962)—and after more than five decades of global environmental governance (UN, 1973), suggesting that something is falling at the core of international environmental policy. When writing this text, in May 2024, carbon dioxide concentration levels in the atmosphere surpassed 420 parts per million (ppm) —see Figure 1.1—, steadily moving away from the level of 350 ppm, which is considered safe for climate stability (Hansen et al., 2008). The year 2023 has been the warmest since registers began; the global temperature of the oceans is at historic highs, and a new record of 40 900 tonnes of CO_2 emitted to the atmosphere has been reached (Greenpeace, 2024). The Intergovernmental Panel on Climate Change, in its last report (IPCC, 2023), details the unprecedented changes that human-induced global warming of 1.1ºC has caused in the planet's climate. According to this body, the security window to address the climate crisis closes with the increased probability of reaching dangerous tipping points in the climate system that can trigger amplified reactions that worsen the situation, such as the melting of permafrost or massive forest fires. Similarly, a recent study states that assuming the current pace of emissions, one of the most prominent climate tipping point elements, i.e. the Atlantic meridional overturning circulation, can potentially collapse, plunging Europe into a new ice glace (van Westen et al., 2024).

While climate change is one of the greatest threats to public health this century, this issue often refers to a narrow and limited focus on emissions and the impacts of the climate crisis, causing the effect of a tunnel vision (Deivanayagamid and Osborneid, 2023) that misses relevant critical aspects of what is already a polycrisis (Lawrence et al., 2024). Nearly halfway between their proposal and the 2030 deadline for their achievement, the Sustainable Development Goals (SDGs) still need to be on track to be attained (Cardini, 2024). On a global scale, many systemic issues and environmental

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* Extract belonging to Moody, R. (2004). El velo negro. DeBolsillo, Barcelona, using a quote from the American writer Nathaniel Hawthorne, p. 298.

problems continue to increase (UN Environment, 2019) following the post-1950 "great acceleration" trend (Steffen et al., 2015), moving further away from sustainability.

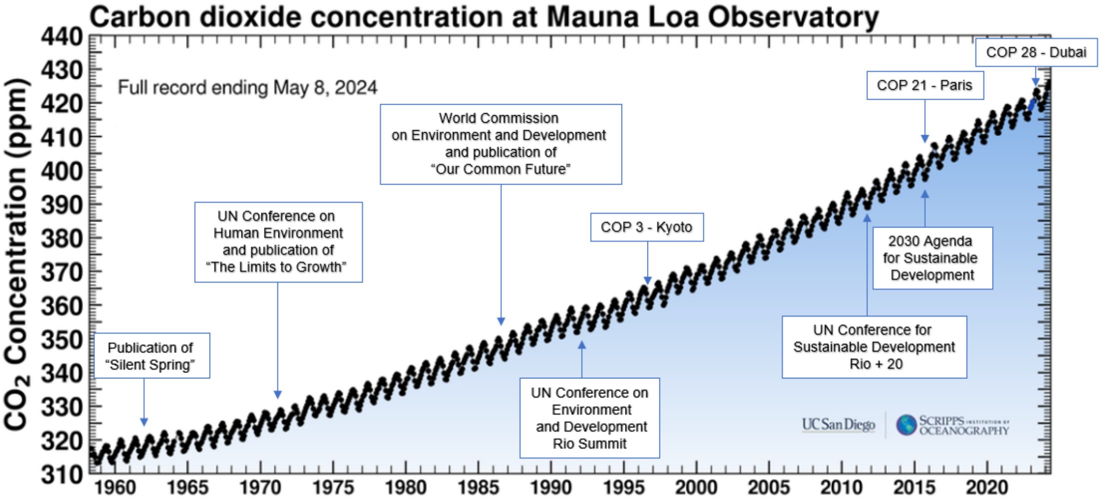

Figure 1.1. Carbon dioxide concentration in the atmosphere, and some keystones of modern environmentalism and environmental governance. Source: own elaboration from Scripps Institution of Oceanography at UC San Diego (2024).

Extraction of materials, energy, and water; waste production; land degradation; and biodiversity loss continue growing, along with economic indicators such as the gross domestic product (GDP), human population, and urbanisation (Haberl et al., 2019). Six of the nine planetary boundaries have been transgressed, pushing natural systems into unsafe operating spaces that threaten the biophysical preconditions upon which human societies can exist, let alone flourish (Richardson et al., 2023). Insofar as the human imprint on earth scales with consumption, the highest-income countries are the main ones responsible for most environmental impacts (Wiedmann et al., 2020) that, on the other hand, affects the populations of the global south more intensely (Long et al., 2023). Perplexedly as it may be, humanity has never before moved so fast from sustainability (Gowdy, 2020). The situation can be worse than expected, with the world entering uncharted territory (Schmidt, 2024). This is why some authors state that we must start discussing post-sustainability scenarios (Benson and Craig, 2014; Foster, 2018; Scranton, 2015).

Although the term "Anthropocene" (Crutzen, 2006) has recently been rejected as a formal unit of geological time (Zhong, 2024), it still provides an invaluable description of human impact on the Earth system. In the same vein, some authors argue the term "Entropocene" provides a more accurate depiction of the human effects on the entire

Earth (Stiegler, 2021). This concept captures the increasing rates of entropy production across various dimensions. In a classic thermodynamic sense, it refers to the degradation of favourable gradients essential for human activity. From a biological perspective, it highlights the ongoing reduction in biodiversity. Finally, an informational narrative emphasises the loss of meaning as knowledge becomes increasingly simplified into mere information and computation. Armiero (2021), for its part, speaks of the "Wasteocene" concerning an era marked by the continuous production of waste partnered with the expansion of people and human activity over the planet. An expansion that also requires considering inequalities and power relations to understand the socioecological crisis. Be that as it may, all these terms stress the idea that the growth of an already supersized consumerism economy and human population is incompatible with long-term functioning ecosystems needed for sustaining life. Precisely, this unsustainable perspective is neglected by hegemonic narratives, values and imaginaries.

It is important to note that the sustainability crisis results from unsustainable production and consumption practices. In other words, paraphrasing the title of a book written by a famous Spanish ecological economist, the roots of ecological and social deterioration are economic[1]. The public at large and mainstream economic professionals, in particular, see economic sustainability as a problem of sustaining capital accumulation. Endless capital accumulation rests on the ceaseless production and reproduction of new wants, needs and desires backed by the ability to pay, simultaneously generating social and environmental degradation (Klitgaard, 2013). However, the dominant presence of the narratives proposed by conventional economics has fostered a distorted worldview in which the functioning of the economy is divorced from the environment (Gómez-Baggethun and Naredo, 2015; Naredo, 2015). Most of the time, environmental problems are systematically ignored or, at best, considered external to the functioning of the economic system that minimal interventions can correct. Thus, conventional economics tend to foster an attitude based on "solutionism" (Morozov, 2013), which holds that these issues have benign solutions that involve technological applications or the use of market-based instruments, ignoring the deep dependence of social and economic structures on a biophysical reality (Spash and Ryan, 2012). In practice, sustainability efforts focus on optimising specific objects or processes, shifting responsibility from collective action to individual choices. This narrow approach neglects broader systemic effects —such as the Jevons paradox— where local improvements

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[1] I mean the book *Raíces económicas del deterioro ecológico y social* (Naredo, 2010).

can unintentionally cause adverse outcomes on a larger scale (Giampietro and Mayumi, 2018). These approaches boost the generation of implausible socio-technical imaginaries (Jasanoff and Kim, 2015) supported by policy legends like the circular economy, decoupling or green growth (Giampietro and Funtowicz, 2020). In this way, our society now shares the belief that continued economic expansion is compatible with our planet's ecology since technical change and substituting production factors according to scarcity and the price mechanism will allow us to decouple GDP growth from resource use and carbon emissions. Unfortunately, there is little evidence that the faith in the possibility of generating significant reductions in resource use or emissions to stay within planetary boundaries is true (Haberl et al., 2020; Hickel and Kallis, 2019; Parrique et al., 2019).

According to Giampietro and Funtowicz (2020), the success of the narratives proposed by conventional economics can be explained not because of its ability to provide insights about how to guide action concerning the sustainability of modern societies but rather because of its capacity to filter out uncomfortable knowledge that could destabilise the actual structure of power. Consequently, a constant "social construction of ignorance" (Rayner, 2012) is produced, removing from the sustainability discussion robust knowledge claims that point out cost-shifting practices, critical tensions between material standards of living and ecological damage or resource stock depletion, among others. In this way, the biophysical challenges determined by the fact that the global economy has moved from operating in an empty world to a full world (Daly, 2005) can be systematically ignored. Alternatively, Swyngedouw (2010) considers that dominant narratives underpinning policy responses to sustainability issues remain overtly apolitical. The author discerns between the "political", i.e. the antagonist struggle between alternative visions of sustainability and the tactics to achieve them, and "policies" as public management solutions focused on technical innovation and managerial aptitudes to pre-framed problems, nothing that there is a tendency for the latter to prevent the former. In this way, the sustainability discourse is articulated around the naturalisation of technocratic approaches where economic growth and free trade are considered the only possible forms of social organisation.

The point is that in sustainability, we deal with wicked problems (Head, 2022; Rittel and Webber, 1973), i.e. complex, interwoven issues that defy simple solutions and an uncontested agreement on the nature of the problem. They demand our collective attention and fair and informed deliberation. From resource depletion to environmental toxins, these wicked problems intertwine in ways that make addressing them in isolation nearly impossible. Moreover, the solution to a problem belonging to a particular dimension usually generates new issues in other dimensions or shifts the damage to the future. For instance, building vast amounts of low-carbon energy-producing and energy-using infrastructure to replace fossil fuels would reduce emissions. Still, it would require huge investments of money and enormous quantities of depleting, non-renewable minerals, the mining of which would generate pollution and destroy wild habitats (Smil, 2016). Another example is synthetic fertiliser, widely introduced to sustain and increase agricultural production (Giampietro and Mayumi, 2009). As a result, modern agriculture has become highly dependent on oil (a non-renewable resource) and petrochemicals. In general, complex sustainability problems inevitably lead to the need for a holistic mode of thinking and make mainstream applications to the handling of environmental issues insufficient (González-Márquez and Toledo, 2020). They need adaptive, multidimensional approaches beyond simplistic notions of resource efficiency and decoupling to understand the complexity of problems and potential responses (Haberl et al., 2021).

“Crisis evinces the failures of understanding and the practical inadequacy of knowledge” (Spash, 2020, p. 45). This sentence synthesises the need for new heuristics in the face of environmental emergencies to analyse the linkages between societies and their resource use quality and quantity. The proposal of this thesis, which I made explicit in the next section, seeks to follow this path, providing valuable and alternative representations on the scientific side, with the hope that this endeavour could have ramifications on the political side (i.e. more effective policies) and the pragmatic side (i.e. more sustainable social practices), offering possibilities for fairer ecological futures that prioritise environmental sustainability and well-being.

1.2. Research objective and my contribution to the debate.

In this thesis, I stand from sociometabolic research and, more specifically, the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach. Sociometabolic research provides an avenue to study human interactions with nature, stressing that environmental degradation is not something alien or external but a byproduct of the operation of our socioeconomic practices (Haberl et al., 2019). It also tackles the sustainability predicament by avoiding reification. The problem to be solved is not about tangible entities (e.g. excessive greenhouse gas emissions) but about a socioeconomic system that promotes unsustainable practices. MuSIASEM, initially proposed by Giampietro and Mayumi (2000a, 2000b), is a complexity-based approach with rich theoretical foundations and different analytical tools that make it suitable for studying complex sustainability problems.

One of the main features of MuSIASEM is that when studying complex systems (e.g. a socioeconomic system), it is essential to acknowledge the existence of both social incommensurability and technical incommensurability:

- Regarding social incommensurability, those proposing a given representation must recognise the unavoidable existence of different social actors, carriers of contrasting and legitimate values, perceptions, and interests when deciding why, what and how to act. This heterogeneity of visions implies that optimal solutions do not (and cannot) exist; the only possibility is to implement an informed and fair political process that acknowledges the unavoidable generation of winners and losers.
- About technical incommensurability, the analysts working on the quantitative and qualitative characterisation of a given issue must acknowledge the impossibility of reducing the various useful representations into a single quantitative model. Complexity implies that lots of indicators are needed (Munda, 2008).

Concerning this double challenge, MuSIASEM tackles the complexity associated with the generation of quantitative models of sustainability issues by: (i) integrating different dimensions (e.g. economic, demographic and biophysical), facilitating a multidimensional analysis that goes beyond the exclusive use of monetary indicators; (ii) considering and integrating different scales of analysis, i.e. the whole, its compartments, and the relation between the whole and other systems; and (iii) combining information referring to non-equivalent descriptive domains, i.e. an external vision and an internal vision as we will see later.

The rich characterisation MuSIASEM provides is closely aligned with the nexus heuristics in the integrated study of interconnected phenomena like the water-energy-food nexus (Brouwer, 2022). The nexus (often short for water-energy-food-environment, or WEFE nexus) has become increasingly popular since its introduction in mainstream sustainability discourses following the Bonn 2011 Nexus Conference (Hoff, 2011). It is a lens needed to view connections between different dimensions of sustainability issues. The nexus approach can be used to endorse research into win-win technological solutions (Cairns and Krzywoszynska, 2016; Stirling, 2015). For instance, improving efficiency and adopting more sustainable crops can increase food production without increasing cultivated land or water use. Within this vision, new advances in biotechnology can improve crop yields, water use efficiency and drought tolerance (D'Odorico et al., 2018). This understanding of the nexus relies on technological fixes as sustainability solutions, as they enable business-as-usual approaches without addressing the fundamental drivers of high-consumption lifestyles (Higgs, 2024). In this context, the proposed win-win solutions advocate for an expansive capitalism in a world assumed to have no limits.

In contrast, the nexus approach can serve as a framework highlighting the impossibility of such techno-optimistic solutions pushing for a change in perspective, defined by Urbinatti et al. (2020) as a "way of viewing problems". This perspective emphasises maintaining Earth's stability by respecting safe thresholds across various processes and systems (Caesar et al., 2024). Sustainability challenges are inherently interconnected, and addressing a single issue in isolation (e.g. climate change) generally leads to unintended consequences such as transgressing other planetary boundaries like land use or waste generation.

This version of the nexus approach is essential for providing a comprehensive critique of reductionist sustainability strategies, such as energy efficiency, green growth, and circular economy models. These approaches frequently focus on isolated improvements while neglecting the interconnectedness of social, economic and environmental systems. By integrating multiple resource flows (e.g. water, energy, food) and funds (e.g. human activity, power capacity, land), the nexus framework reveals the inherent trade-offs and limitations of optimisation strategies, showing that gains in one domain intensify pressures in others. In this sense, this nexus approach challenges hegemonic win-win solutions by exposing how they often overlook systemic trade-offs and resource constraints, thereby perpetuating growth-oriented models that overlook the finite nature of Earth's resources and absorption capacities. It calls for transformative change, urging a rethinking of societal structures and priorities. Moreover, its commitment to biophysical limits and the complex interdependencies underpinning true sustainability underscores scientific knowledge's boundaries, refusing the stance of scientific control imbued with certainty (Bonneuil and Fressoz, 2016).

In this thesis, I build on this second conception of the nexus. Consequently, I am not seeking a final answer to the sustainability problem or magical solutions. Conversely, adopting a post-normal science perspective (Funtowicz and Ravetz, 1993), which acknowledges the existence of irreducible uncertainty and epistemic pluralism, I adopt a systemic approach that aims to transform perceptions and representations of society-nature interactions into a more holistic understanding. This perspective entails recognising the existence of biophysical limits of different nature.

In short, the main research objective of this thesis is to articulate a sound sustainability analysis that explicitly acknowledges (i) the dependence of our economies on the natural macro system, (ii) the fact that what matters for a sustainable relationship is the use of materials and energy compatible with ecosystem's maintenance, renewal, and assimilation capacity, and (iii) the effect of our political choices on the desirability of our social practices. This analysis should provide a more informed discussion about what is possible or desirable in the sustainable development domain, avoiding "hypocognition" (Lakoff, 2010), i.e. the omission of relevant aspects for adaptation and sustainability determined by adopting simplistic descriptions often found in conventional analyses.

My research objective is approached at two levels, methodological and analytical:

- **Methodologically**, I first critically appraise conventional economics when studying sustainability. Then, I discuss the appropriateness of MuSIASEM to address sustainability issues, delving into the theoretical foundations of the approach and offering a detailed overview of the analytical tools within the methodology designed to assess various aspects of the current sustainability crisis. Lastly, I mention some practical examples where the methodology has been applied and clarify some limitations of such a protocol.
- **Analytically**, I apply the set of different epistemological tools developed in the latest version of MuSIASEM to the case study of Andorra, aiming to provide a comprehensive understanding of its sustainability. This analytical endeavour serves a dual purpose: (i) generating valuable descriptions by considering Andorra as a social-ecological system which involves integrating different types of information and data as well as considering different scales and dimensions; and (ii) analysing the framing of the country's sustainability policy discussion, with a focus on the existing narratives.

The choice of Andorra as a case study is interesting beyond the militant particularism (Harvey, 2001) of wanting to translate global problems into where you live. Andorra is a small country located in the Pyrenees. As a mountain area, Andorra is significantly affected by climate change (Miquel et al., 2021). Effects are already noticeable, with an increase in the annual average temperature of 0.21ºC/decade and a decrease in the average yearly rainfall of 22.01 mm/decade from 1950 to 2019 (OECC, 2021). About 40% of the territory of Andorra is covered with forests (CENMA-IEA, 2012), which can be affected by climate change, causing changes in their structure, composition, and health status (OPCC, 2024). The country's rich biodiversity is also susceptible to being affected by climate change (Aubret and Largier, 2022), which will have consequences for the maintenance of natural heritage. Moreover, the trend towards a drier climate will modify its hydrological regime, producing solid reductions in the country's snow cover (Beguería, 2023).

During the twentieth century, the country underwent a dramatic transformation from a subsistence rural economy to an urban economy specialised in the service sector, mainly in tourism and financial activities, implicating the country in global flows of capital and people (Lluelles and García, 2018). At the same time, these radical structural changes are contributing to ecological degradation. Its growth-oriented economy and the improvement of mobility and communication technologies have increased the number of permanent and temporary residents, tourists, and seasonal workers, resulting in an overall increase in the consumption of food, energy, water and other materials.

Currently, the country is at the crossroads. On one side, economic activities centred on winter tourism face increasing challenges to their viability due to their high sensitivity to changes in weather and snow availability (Pons et al., 2014). In addition, an economy heavily reliant on the tourism sector is particularly vulnerable to disruptions from geopolitical events or health crises, as highlighted by the war in Ukraine and the COVID pandemic. Conversely, the transition to a more sustainable model, driven partly by the necessity to meet international commitments such as the Paris Agreement, will require significant structural adaptation measures (OECC, 2021). In any case, determining the main biophysical requirements to maintain the country and express its behaviour is needed before embarking on structural changes. Moreover, Andorra's choice is the basis for working on an easy-to-study system within the European orbit. Due to its relative simplicity and unique blend of country and city characteristics, it is an ideal study case that can provide valuable insights for metabolic assessments of larger

EU countries or urban areas to gain an in-depth understanding of biophysical requirements and interdependencies.

1.3. Research questions and structure of the thesis.

According to the above explanation, I am trying to answer the following research gap:

- ➢ How can a meaningful sustainability analysis be designed to account for critical relationships between society and the environment while addressing various types of limits?

This research gap is closely linked with the following research questions:

- ◊ Is it possible to avoid the excessive simplifications of conventional economics when studying the sustainability of a given social-ecological system?
- ◊ How does MuSIASEM provide a more effective approach to sustainability analysis?
- ◊ Do the results from Andorra’s case study demonstrate the effectiveness of the proposed approach?

This last question can be re-stated in three more specific questions:

- o What are the main biophysical requirements determining Andorra's sustainability?
- o To what extent does the country rely on trade to externalise end uses and environmental pressures to other places?
- o Can the available information referring to different scales and dimensions of analysis be integrated into the Andorran policy-making process?

To answer these questions, this thesis follows the structure shown in Figure 1.2. After reading each chapter, an implicit question emerges and is responded to in the next chapter. This way, this introduction flags to the interested reader the main limitations of the analysis of conventional economics when applied to sustainability problems and why new approaches are necessary. Chapter 2 addresses this issue in detail by providing a detailed critique of conventional economics. At the end of Chapter 2, the subsequent question of how to approach sustainability analysis differently arises, which is tackled in Chapter 3. Chapter 4 answers how to analyse a specific case, in our particular case, Andorra, using the MuSIASEM methodology, focusing on characterising the biophysical requirements for maintenance and reproduction. After this analysis, the next question is to know to what extent these requirements depend on other territories. This is what Chapter 5 is about. Building on this analysis, Chapter 6 examines how current policy discourse addresses this dependence and other critical issues in the Andorran sustainable development domain. Finally, the thesis concludes with a summary of the findings. This structure aims to ensure maximum internal coherence and semantic clarity throughout the thesis.

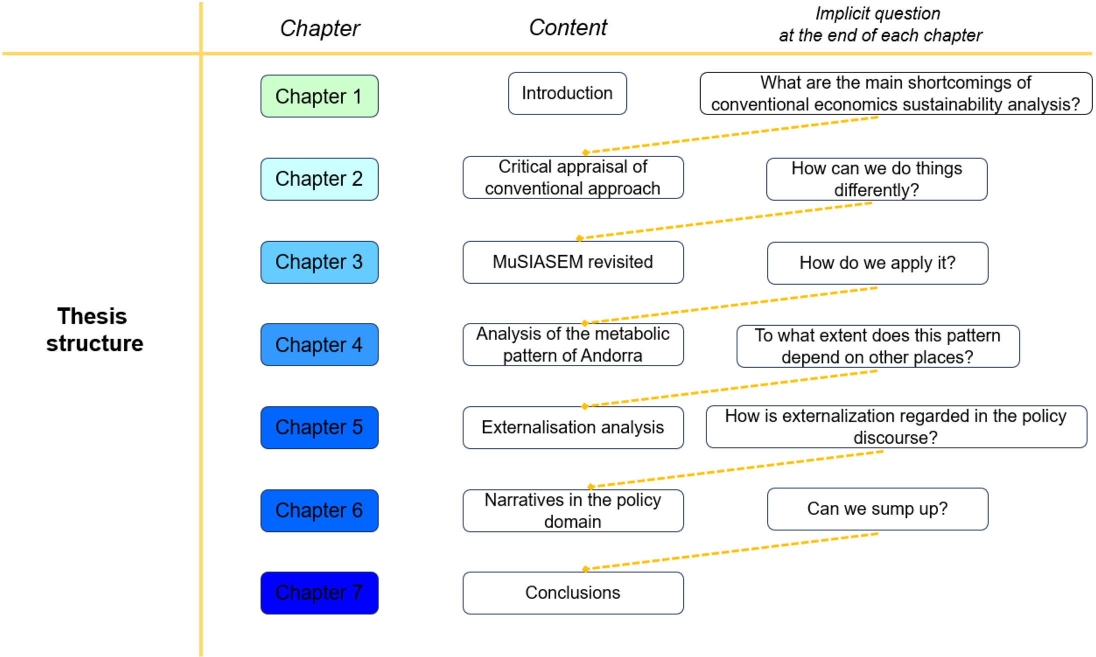

Figure 1.2. Thesis structure.

1.4. Specific outline of the chapters.

After outlining the structure of the thesis, this section provides a detailed overview of what the reader can expect to find in each chapter.

Chapter 1 refers to the introductory section that you are already reading.

Chapter 2 begins by describing the fundamental vision of conventional economics concerning the economic process and the role it assigns to the environment. Subsequently, it stresses the main problems associated with conventional economics' standard procedures for addressing environmental issues, which are, on the one hand, theoretical and, on the other hand, raise intergenerational, incommensurability, institutional and financial concerns. After identifying shortcomings, the chapter introduces the fundamental vision of ecological economics as a valuable vision for studying society-nature interactions. The chapter also helps to place the selected methodology, MuSIASEM, within the sociometabolic research as a paradigm faithful to ecological economics' founding principles.

Chapter 3 synthesises MuSIASEM's primary rationale, clarifying its interpretation of social-economic systems, the economic process and the sustainability predicament. The chapter also revisits and updates the robustness of its theoretical foundations, examining and discussing the concepts combined in the analytical framework. In addition, it summarises the different analytical tools available to the methodology, such as the metabolic processor, the end-use matrix, and the environmental pressure matrix, concerning the latest case studies where they have been applied for an integrated and meaningful sustainability analysis across different dimensions and scales. An important conclusion of this chapter is that, unlike conventional economic analysis, the selected methodology allows mapping the relationships established: (i) within the "black box" of the economy, describing the internal interactions using the end-use matrix; (ii) between the economy and the embedding natural systems, capturing the "black box" versus environment interactions using the environmental pressure matrix; and (iii) between the local economy and other economies through international trade, highlighting the externalisation of end uses and environmental pressures to other social-ecological systems. For this reason, it is a valuable tool to carry out sound analyses in sustainability science.

Chapter 4 starts the analytical part of the thesis by examining the metabolic pattern of Andorra. It characterises Andorra as a dissipative structure, i.e. an open metabolic system whose structures and functions are stabilised by a continuous flow of inputs taken from the environment (e.g. energy and materials) and a constant flow of outputs released to the environment (e.g. wastes and emissions) which leads to the generation of pressures on the environment. Then, a diagnosis of Andorra's biophysical performance is accomplished. This task implies defining the country's boundaries and the different societal compartments inside Andorra, i.e., its functional parts. In this regard, this chapter considers the household sector (HH), the paid work sector (PW), and within the latter, the agricultural sector (AG), the industry, construction, and manufacturing sector (ICM), and the service and government sector (SG). Quantitative information is required for these different levels of analysis to characterise: (i) the consumption of energy carriers such as electricity, fuels and heat; (ii) the consumption of water (keeping the distinction between consumptive and non-consumptive use); (iii) the generation of greenhouse emissions; (iv) the amount of solid waste produced; (v) the value in EUR millions of the goods and services produced in the PW; (vi) the human activity (in hours), both labour in the PW and household practices, devoted to each level of analysis; and (vii) the land uses (in hectares) associated to the whole country, and each defined societal compartment. All this information is integrated using an end-use matrix and an environmental pressure matrix to describe Andorra's functions and assess its sustainability. Subsequently, based on the quantitative information generated, the chapter provides a metabolic comparison of Andorra with its neighbouring countries and the average of the European Union, on the one hand, and with another area of functional solid specialisation in tourist activities, such as the island of Menorca, on the other hand.

Chapter 5 examines Andorra's metabolic pattern's dependence on external territories. This task involves analysing the interdependence between Andorra's exosomatic metabolism (related to energy security) and endosomatic metabolism (associated with food security) in relation to local production, local consumption, and imports. Andorra's metabolic pattern tied to its functional identity is described using an end-use matrix, considering this time energy endosomatic and exosomatic requirements. Subsequently, externalisation is characterised by comparing the labour, land use, water, and greenhouse emissions associated with Andorra's energy and agricultural systems to the expected values of these variables embodied in the imported energy and food commodities, calculated using metabolic processors. Findings in this chapter also raise essential considerations regarding decarbonisation policies and ethical concerns, prompting a critical evaluation of whether current sustainability policies are improving the system's performance or merely shifting problems elsewhere.

Chapter 6 shifts the focus from a purely quantitative analysis to examining how issues are framed in Andorra's sustainable development domain discourse. The main goal of this chapter is to contrast the conventional framing —characterised by a specific set of narratives, policies, and indicators— with an alternative framing that employs the metabolic approach developed in this thesis. This alternative quantitative storytelling implies that we should consider using alternative narratives and indicators and implementing different policies. Therefore, new insights can emerge by comparing different approaches (i.e., the conventional versus the metabolic) associated with different pre-analytical choices and representations on the scientific side, contributing to a more informed discussion about the current policy discourse in the sustainability field.

Chapter 7 serves as the conclusion, beginning with answers to the research questions. It also summarises critical methodological insights and significant findings from Andorra's case study and outlines directions for future research.

Appendix A provides information about the statistical data and reports used to perform the biophysical diagnosis presented in Chapter 4. MuSIASEM analyses need to combine quantitative information from different dimensions, and this issue often requires struggling against the lack of coherence of different sources. Moreover, it clarifies different working assumptions, such as the percentage of tourists who are considered staying in hotels (i.e., human activity allocated to the SG) compared to those who do so in private homes (i.e., human activity given to the HH). It also addresses the percentage of gasoline and diesel imports not used for domestic consumption (in the HH or PW sectors) but sold as fuel tourism, given the lower price in Andorra compared to its neighbouring countries. Reports, statistical data, and previous scientific works support these assumptions.

Appendix B provides information about how the quantitative information concerning the externalisation analysis presented in Chapter 5 has been produced. For the accounting of the biophysical elements embodied in energy and food products, Spain and France's electricity generation mixes have been considered for imported electricity, Spain's refining mix for oil products, and Spain's technical coefficients of food production for imported agricultural products. Readers can check this appendix for data on externalised production processes (e.g. how much water or working hours a hypothetical nuclear plant uses to produce electricity or how much water and working hours are needed to make a tone of potatoes) as well as data about the structural mix considered (e.g. what percentage of the gas used in a combined power plant to produce electricity is extracted offshore, and how much onshore). They can also verify the assumptions used to describe Andorra's energy and agricultural systems.

Appendix C reproduces a text published in the "*XVII Jornadas de Economía Crítica*" proceeding book, held in Santiago de Compostela on 4 and 5 February 2021. It is an excellent introductory text of MuSIASEM for readers who prefer to read in Spanish.

Finally, Appendix D includes a glossary of terms used in this thesis to facilitate quick reference.

1.5. Reflections about my positionality.

In late 2018, I embarked on my thesis journey with the guidance of Mario Giampietro and Raúl Velasco. My primary aim was to gain a deeper understanding of sustainability science from an ecological economics perspective using MuSIASEM. However, I quickly realised that comprehending MuSIASEM was a formidable task, given its deep roots in complex system theory and theoretical ecology. This was particularly challenging for me, coming from a background in conventional economics. Despite these challenges, my determination to push beyond established methods and explore new directions remained steadfast.

For this reason, the directors (at that moment, supervisors) found it convenient that my initial research efforts focused on preparing a theoretical dictionary with definitions and references to face, in the best conditions, the methodological framework of the thesis. This endeavour served as the basis for an in-depth understanding of the theoretical concepts and seminal authors of the study of social metabolism in general and the selected methodology in particular. It also marked the collaborative working relationship between Mario, Raúl and me, characterised by high demands, flexibility, and fraternity. So, my initial writing of a draft was reviewed and thoroughly improved by them while it was proposed to make "*otra vuelta*" in search of new improvements. This latest version was revised, and at the end of the revision, we gave it "*otra vuelta*" and again until obtaining the final version in an always intense and extensive process. The outcome of this initial work was a revised interpretation of the theoretical foundations of MuSIASEM, which strengthens the connection between the approach's theoretical roots and its practical applications. This effort led to my participation in the "*XVII Jornadas de Economía Crítica*" and the publication of a text in Spanish on MuSIASEM, which is included as Appendix C.

Following this line, the logical next step was to publish an article in English on the theoretical foundations of the methodology. I chose the journal Ecological Economics due to its thematic affinity and began an intense writing process until I obtained a definitive version. However, the manuscript was rejected in the peer review process, with reviewers noting its engaging but hermetic nature. This setback led to rewriting and intense revision with the directors, significantly delaying the thesis schedule. The revised manuscript was submitted to Sustainability Science, Environment, Development and Sustainability and Ecological Complexity journals. The different editors rejected it because it did not fit into the journals' line. These experiences underscored the challenge of publishing a theoretical text of a heterodox methodology in an indexed scientific journal, mainly when the writer is a doctoral student like myself.

Seen in retrospect, this was undoubtedly the most tedious and frustrating period of the doctorate, which, in part, coincided with the socio-sanitary crisis promoted by COVID-19. The loneliness of the long-distance runner working on a doctorate in Andorra with the present companion of the Pyrenees mountains and the difficulties of publishing added an unexpected global situation for all, which created a few more degrees of isolation and family burdens for everyone. I read somewhere that a "PhD is a test of tenancy", and indeed, this statement proved to be true. It is about resisting and being there despite everything. This is how I perceived Academia in this troubled period.

Ultimately, I published the article in the Journal of Critical Economics. I believe that the final result is quite worthy. The magazine's editorial team treated the article excellently, and the final article improved significantly with the constructive suggestions of two anonymous reviewers. Chapter 3 of this thesis faithfully adapts it.

In parallel to the methodological efforts, the initial nexus quantification was also carried out in the first attempt to understand the reality of Andorra through the lens of MuSIASEM. This process involved combining separate pieces of information to get a more holistic view. Also, ensure comparability with other previous work performed. Despite encountering some difficulties and inconsistencies concerning data sources, this process was smoother and benefited from all the theoretical work used to explain the numbers more confidently. The Progress Report defended in June 2021 and Chapter 4 of this thesis are proofs.

On the contrary, the externalisation analysis, which examines Andorra's dependence on other territories, posed significant challenges in data collection. The energy and agricultural systems of Andorra required a level of detail that was often not available in the reports published by the different companies or institutions. For example, it was difficult to determine the number of employees directly involved in the operation and maintenance of Andorra's power plants within the energy sector. Similarly, reliable values for land use were not readily accessible. These data gaps highlight the need for further data transparency. Most values used were obtained from reports when the information was publicly available. Conversely, data not found was estimated based on theoretical values, specific assumptions, or discussions with local experts. Moreover, given the number of externalised production processes related to imported food and energy commodities, getting biophysical data from scratch required a steep learning curve and economic costs. For instance, I tried to become familiar with Ecoinvent (Frischknecht et al., 2007), but this task also involved paying a fee to access the full mode. Thus, after some research, the required information about inputs and outputs was obtained from the secondary datasets Cadillo-Benalcazar and Renner (2020) and Di Felice (2020) developed from an earlier project inside the MuSIASEM group called MAGIC (Giampietro et al., 2020), which provides an exceptional starting point for the realisation of biophysical analyses.

Special mention requires the accounting for the biophysical elements embodied in food imports. The variety of food commodities —raw customs data obtained thanks to a collaboration with Andorra Research & Innovation listed more than 1 400 Excel rows with different combined nomenclature (CN) codes— the complexity of livestock systems and the diverse options for livestock diets led to “heroic assumptions” concerning quantification (e.g. which vegetables to include or which feed types consider). In this sense, the analysis of biophysical requirements for food imports for the particular case study of Andorra is an approximation that underestimates actual needs due to missing categories (e.g. alcoholic beverages), the consideration of milk and eggs as byproducts and the disregarding of specific feed categories to avoid double accounting (e.g. the accounting of soybean and soybean byproducts like soybean oil). Chapter 5 is the completion of this effort together with an article currently in the process of review in the journal Ecological Economics titled “Using MuSIASEM to characterise the metabolic pattern of Andorra and its dependence on imports”.

The last months of writing the thesis, late 2023 and the first semester of 2024, were the ones I enjoyed the most. I am especially proud of Chapter 6, where I felt confident relating different concepts learned during the thesis and explaining them with some numerical examples. Chapter 2 of the thesis also benefited from parallel work at Carlemany University, where I teach environmental and ecological economics classes. Unfortunately, I ran out of time against the submission deadline. For reasons I do not know, in my last request for a six-month extension, I was only given two and a half months, during which I had to finish the final thesis document in a frantic summer.

This thesis stresses the need to consider different dimensions when understanding sustainability. The truth is that writing this thesis has been an effort to combine obligations in various dimensions: academic deadlines, family care, and maintaining my mental and physical health. So, dear reader, here is the result of all this effort. The outcome is humble because my gaze can only be valid by recognising many other possible perspectives. It is also open to new possibilities, as evidenced in the future research summarised in the conclusion section.

1.6. Related work.

Publications

Larrabeiti-Rodríguez, J.J., Velasco-Fernández, R., Giampietro, M., 2021. MuSIASEM: una metodología para el estudio de las bases biofísicas de los sistemas socioeconómicos desde la complejidad, in: Dios-Vicente, A., Rios-Rodríguez, R. (Eds.), Libro de Actas XVII Jornadas de Economía Crítica: "Emergencias, Transiciones y Desigualdades Socioeconómicas." AEC-Asociación de Economía Crítica, Santiago de Compostela, pp. 293-322.

Larrabeiti-Rodríguez, J.J., Velasco-Fernández, R., 2022. Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) revisited: synthesizing and updating the theoretical foundations. Journal of Critical Economics 34, 44-68.

Larrabeiti-Rodríguez, J.J., Travesset-Baro, O., Velasco-Fernández, R., Giampietro, M., (under review). Using MuSIASEM to characterise the metabolic pattern of Andorra and its dependence on imports. Ecological Economics.

Conference Presentations

"MuSIASEM: Una metodología para el estudio de las bases biofísicas de los sistemas socioeconómicos desde la complejidad". XVII Jornadas de Economía Crítica, University of Santiago de Compostela, 4-5 February 2021.

"The metabolic pattern of Andorra". Liphe4 Summer School 2023 Edition: Energy transitions, diagnosing wishful thinking and identifying critical vulnerabilities, ICTA-UAB, 10-14 July 2023.

"Characterising endosomatic and exosomatic metabolism's performance and dependence on externalised processes using MuSIASEM: The case of Andorra". 10th International Degrowth Conference and 15th Conference of the European Society for Ecological Economics (ESEE), University of Vigo, 18-21 June 2024.

"La sostenibilitat d'Andorra des de una perspectiva metabòlica". 16ns Debats de Recerca, Aigua: desafiaments i oportunitats. Govern d'Andorra i Societat Andorrana de Ciències, 11-12 November 2024.

1.7. Chapter references.

Armiero, M., 2021. Wasteocene: Stories from the global dump. Cambridge University Press, Cambridge.

Aubret, F., Largier, G., 2022. Guía de recomendaciones para los planes de gestión de la flora y la fauna en un contexto de cambio climático. CNRS SETE, Conservatoire botanique national Pyrénées et Midi-Pyrénées, Vallon de Salut.

Beguería, S. (Eds), 2023. Caracterización de los recursos hídricos de los Pirineos en la actualidad, y escenarios futuros. Consejo Superior de Investigaciones Científicas, Zaragoza.

Benson, M.H., Craig, R.K., 2014. The End of Sustainability. Soc. Nat. Resour. 27, 777–782. https://doi.org/10.1080/08941920.2014.901467

Bonneuil, C., Fressoz, J.B., 2016. The shock of the Anthropocene: The earth, history and us. Verso, London-New York.

Brouwer, F. (ed), 2022. Handbook on the water-energy-food nexus. Edward Elgar Publishing, Cheltenham.

Cadillo-Benalcazar, J.J., Renner, A., 2020. Top-down and bottom-up vegetal and animal product metabolic profiles for 29 European countries (EU27 + United Kingdom + Norway) [dataset] [WWW Document]. Zenodo. https://doi.org/10.5281/ZENODO.3923010 (accessed 10 February 2022)

Caesar, L., Sakschewski, B., Andersen, L.S., Beringer, T., Braun, J., Dennis, D., Gerten, D., Heilemann, A., Kaiser, J., Kitzmann, N.H., Loriani, S., Lucht, W., Ludescher, J., Martin, M., Mathesius, S., Paolucci, A., te Wierik, S., Rockström, J., 2024. Planetary Health Check Report 2024. Potsdam Institute for Climate Impact Research, Potsdam.

Cairns, R., Krzywoszynska, A., 2016. Anatomy of a buzzword: The emergence of 'the water-energy-food nexus' in UK natural resource debates. Environ. Sci. Policy 64, 164–170. https://doi.org/10.1016/J.ENVSCI.2016.07.007

Cardini, A., 2024. Unsustainable Development Goals. Ecol. Citiz. 7, epub-108.

Carson, R., 1962. Silent Spring. Houghton Mifflin, Boston.

CENMA-IEA, 2012. Mapes de cobertes del sol d'Andorra [WWW Document]. URL https://www.iea.ad/mapa-de-cobertes-del-sol-d-andorra-2012 (accessed 12 Desember 2020).

Crutzen, P.J., 2006. The “Anthropocene,” in: Ehlers, E., Krafft, T. (Eds.), Earth System Science in the Anthropocene. Springer, Berlin, pp. 13–18. https://doi.org/10.1007/3-540-26590-2_3

D’Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell’Angelo, J., Gephart, J., MacDonald, G., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56. https://doi.org/10.1029/2017RG000591

Daly, H., 2005. Economics in a full world. Sci. Am. 293, 78–85.

Deivanayagamid, T.A., Osborneid, R.E., 2023. Breaking free from tunnel vision for climate change and health. PLOS Glob. Public Heal. 3, e0001684. https://doi.org/10.1371/JOURNAL.PGPH.0001684

Di Felice, L.J., 2020. Energy systems as holarchies: Complexity and sustainability across scales [dataset] [WWW Document]. Zenodo. https://doi.org/http://doi.org/10.5281/zenodo.4271325 (accessed 10 February 2022)

Foster, J., 2018. Post-Sustainability: Tragedy and Transformation. Routledge, Abingdon.

Frischknecht, F., Jungbluth, N., Althaus, N., Doka, G., Heck, T., Hellweg, S., Hirschier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2007. Overview and methodology. Final Report Ecoinvent data v. 2.0. Dübendorf.

Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age. Futures 25, 735–755.

Giampietro, M., Cadillo-Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez-Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliverable 4.4, 30 August 2020.

Giampietro, M., Funtowicz, S., 2020. From elite folk science to the policy legend of the circular economy. Environ. Sci. Policy 109, 64–72. https://doi.org/10.1016/j.envsci.2020.04.012

Giampietro, M., Mayumi, K., 2018. Unravelling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026

Giampietro, M., Mayumi, K., 2009. The Biofuel Delusion: The fallacy of large scale agro-biofuels production. Routledge, London.

Giampietro, M., Mayumi, K., 2000a. Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. Popul. Environ. 22, 155–210. https://doi.org/10.1023/A:1026643707370

Giampietro, M., Mayumi, K., 2000b. Multiple-scale integrated assessment of societal metabolism: introducing the approach. Popul. Environ. 22, 109–153. https://doi.org/10.1023/A:1026691623300

Gómez-Baggethun, E., Naredo, J.M., 2015. In search of lost time: the rise and fall of limits to growth in international sustainability policy. Sustain. Sci. 10, 385–395. https://doi.org/10.1007/S11625-015-0308-6/METRICS

González-Márquez, I., Toledo, V.M., 2020. Sustainability Science: A Paradigm in Crisis? Sustainability 12, 2802. https://doi.org/10.3390/su12072802

Gowdy, J., 2020. Our hunter-gatherer future: Climate change, agriculture and uncivilization.

Futures 115, 102488. https://doi.org/10.1016/J.FUTURES.2019.102488

Greenpeace, 2024. 2023 un año record de eventos climáticos extremos y de emisiones de C02. Madrid.

Haberl, H., Schmid, M., Haas, W., Wiedenhofer, D., Rau, H., Winiwarter, V., 2021. Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism. Ecol. Econ. 182, 106949. https://doi.org/10.1016/J.ECOLECON.2021.106949

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., Creutzig, F., 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ. Res. Lett. 15, 065003. https://doi.org/10.1088/1748-9326/AB842A

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, J.C., 2008. Target atmospheric CO2: Where should humanity aim? Open Atmos. Sci. J. 2, 217–231. https://doi.org/10.2174/1874282300802010217

Harvey, D., 2001. Militant particularism and global ambition: the conceptual politics of place, space, and environment in the work of Raymond Williams, in: Spaces of Capital. Routledge, New York, pp. 158–187.

Head, B.W., 2022. Wicked Problems in Public Policy: Understanding and Responding to Complex Challenges. Palgrave Macmillan, Cham.

Hickel, J., Kallis, G., 2019. Is Green Growth Possible? New Polit. Econ. https://doi.org/10.1080/13563467.2019.1598964

Higgs, T., 2024. What are we aiming for? Addressing the knowledge gap of a long-term sustainable society. Environ. Sci. Policy 161, 103895. https://doi.org/10.1016/J.ENVSCI.2024.103895

Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm.

IPCC, 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva.

Jasanoff, S., Kim, S.H., 2015. Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power. University of Chicago Press, Chicago.

Klitgaard, K., 2013. Heterodox Political Economy and the Degrowth Perspective. Sustainability 5, 276–297. https://doi.org/10.3390/SU5010276

Lawrence, M., Homer-Dixon, T., Janzwood, S., Rockstöm, J., Renn, O., Donges, J.F., 2024. Global polycrisis: the causal mechanisms of crisis entanglement. Glob. Sustain. 7, e6. https://doi.org/10.1017/SUS.2024.1

Lluelles, M.J., García, E., 2018. Història econòmica d’Andorra, segles XX-XXI. Universitat d’Andorra, Sant Julià de Lòria (Andorra).

Long, M., Lynch, M., Stretesky, P., 2023. Handbook on Inequality and the Environment. Edward Elgar Publishing, Cheltenham.

Miquel, C., Cuyàs, M., Boneta, A., 2021. Cuarto informe bianual de actualización de Andorra ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Govern d’Andorra, Andorra la Vella.

Morozov, E., 2013. To save everything, click here: The folly of technological solutionism. PublicAffairs, New York.

Munda, G., 2008. Social Multi-Criteria Evaluation for a Sustainable Economy. Springer, Berlin.

Naredo, J.M., 2015. La Economía en Evolución : Historia y Perspectivas de las Categorías Básicas del Pensamiento Económico (4ªed.). Siglo XXI, Madrid.

Naredo, J.M., 2010. Raíces económicas del deterioro ecológico y social. Siglo XXI, Madrid.

OECC, 2021. Estratègia energètica nacional i de lluita contra el canvi climàtic 2020-2050. Oficina de la Energia i el Canvi Climàtic, Andorra la Vella.

OPCC, 2024. The CANOPEE project [WWW Document]. Observatori Pirinenc del Canvi Climàtic. URL https://www.opcc-ctp.org/en/canopee (accessed 24 October 2024)

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Koukkanen, A., Spangenberg, J.H., 2019. Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability. A study edited by the European Environmental Bureau, Brussels.

Pons, M., López-Moreno, J.I., Esteban, P., Macià, S., Gavaldà, J., García, C., Rosas-Casals, M., Jover, E., 2014. Influencia del cambio climático en el turismo de nieve del Pirineo. Experiencia del proyecto de investigación NIVOPYR. Pirineos. Rev. Ecol. Montaña 169. https://doi.org/10.3989/Pirineos.2014.169006

Rayner, S., 2012. Uncomfortable knowledge: the social construction of ignorance in science and environmental policy discourses. Econ. Soc. 41, 107–125. https://doi.org/10.1080/03085147.2011.637335.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9. https://doi.org/10.1126/SCIADV.ADH2458/SUPPL_FILE/SCIADV.ADH2458_SM.PDF

Rittel, H.W., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169. https://doi.org/10.1007/BF01405730

Schmidt, G., 2024. Climate models can’t explain 2023’s huge heat anomaly — we could be in uncharted territory. Nature 627, 467–467. https://doi.org/10.1038/D41586-024-00816-Z

Scranton, R., 2015. Learning to Die in the Anthropocene: Reflections on the End of a

Civilization. City Lights Publishers, San Francisco.

Scripps Institution of Oceanography, 2024. The Keeling Curve - Full Record [WWW Document]. https://keelingcurve.ucsd.edu/ (accessed 8 May 2024)

Smil, V., 2016. What i see when i see a wind turbine [Numbers Don't Lie]. IEEE Spectr. 53, 27. https://doi.org/10.1109/MSPEC.2016.7420393

Spash, C.L., 2020. A tale of three paradigms: Realising the revolutionary potential of ecological economics. Ecol. Econ. 169, 106518. https://doi.org/10.1016/j.ecolecon.2019.106518

Spash, C.L., Ryan, A., 2012. Economic Schools of Thought on the Environment: Investigating Unity and Division. Cambridge J. Econ. 36, 1091–1121. https://doi.org/10.1093/CJE/BES023

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015. The trajectory of the Anthropocene: The Great Acceleration. Anthr. Rev. 2, 81–98. https://doi.org/10.1177/2053019614564785

Stiegler, B., 2021. Bifurcate: There Is No Alternative. Open Humanities Press, London.

Stirling, A., 2015. Developing 'Nexus Capabilities': towards transdisciplinary methodologies (Version 1). Brighton.

Swyngedouw, E., 2010. Impossible Sustainability and the Post-political Condition, in: Cerreta, M., Concilio, G., Monno, V. (Eds.), Making Strategies in Spatial Planning. Urban and Landscape Perspectives, Vol 9. Springer, Dordrecht, pp. 185–205. https://doi.org/10.1007/978-90-481-3106-8_11

UN, 1973. Report of the United Nations Conference on the Human Environment. United Nations, New York.

UN Environment, 2019. Global Environment Outlook (GEO-6): Summary for Policymakers. Cambridge University Press, Nairobi. https://doi.org/10.1017/9781108639217

Urbinatti, A.M., Dalla Fontana, M., Stirling, A., Giatti, L.L., 2020. 'Opening up' the governance of water-energy-food nexus: Towards a science-policy-society interface based on hybridity and humility. Sci. Total Environ. 744, 140945. https://doi.org/10.1016/J.SCITOTENV.2020.140945

van Westen, R.M., Kliphuis, M., Dijkstra, H.A., 2024. Physics-based early warning signal shows that AMOC is on tipping course. Sci. Adv. 10, 1189. https://doi.org/10.1126/SCIADV.ADK1189/SUPPL_FILE/SCIADV.ADK1189_SM.V1.PDF

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 3107. https://doi.org/10.1038/s41467-020-16941-y

Zhong, R., 2024. Geologists Make It Official: We're Not in an 'Anthropocene' Epoch [WWW Document]. New York Times. https://www.nytimes.com/2024/03/20/climate/anthropocene-vote-upheld.html (accessed 11 August 2024)

Chapter 2

2. Fundamental visions: the distinction between conventional economics and ecological economics through the lens of sociometabolic research.

> “La doctrina económica dominante
> es un sofisticado aparato intelectual
> para la legitimación de la codicia”.
> Jorge Riechmann[*].

2.1. Introduction.

This thesis is built around the acknowledgement of the existence of an observer’s point of view, a crucial aspect of scientific inquiry that must be duly considered. This remark is critical when dealing with policy-relevant scientific analysis. In modern complex societies, individuals voice a myriad of concerns, hopes, and fears while having access to fragmented, contradictory, and marginal knowledge of the factors shaping their social practices. Amidst this widespread feeling of heterogeneous perceptions, societal myths (Giampietro, 2024) and socio-technical imaginaries (Jasanoff and Kim, 2015) act as epistemological devices needed to give a sense of control over social facts in the political sphere. These dominant imaginaries are required in order to provide legitimacy to the knowledge claims endorsed by society about the aspects of reality that should be considered relevant when deciding on action (Hausknost, 2023).

About this point, when we look at mainstream narratives endorsed and the priorities expressed or goals pursued at the moment in our society, it is hard to see much evidence of awareness of the ecological crisis presented in the previous chapter. There is a gap between the scale of the processes determining the emergency and the size of the processes trying to respond. This incongruence results from a dominant conceptual model about the environment that is radically inadequate. The point to be made here is that the present prevalence of the core assumptions proposed by conventional economics has produced a distorted worldview, what Macy and Johnstone (2012) call a “Business as Usual story”, where social and economic structures’ dependence on a biophysical reality has been blurred and systematically ignored (Spash and Smith, 2019). The consequences of this fact are becoming painfully evident to those who want to see them: the hegemonic statements driving social-economic systems are based on the

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[*] Extract from *Lo llaman eficiencia y no lo es*, in Riechmann, J. (2013). Fracasar mejor (fragmentos, interrogantes, notas, protopoemas y reflexiones). Olifante, Zaragoza, p. 61.

optimisation of processes, innovation, and globalisation through trade, always seeking more productivism without questioning resource depletion and environmental contamination associated with economic growth (Victor, 2015); nature is commodified (Kallis et al., 2013); overconsumption is promoted (Wiedmann et al., 2020); and the distribution of wealth is increasingly unequal (Chancel, 2022). The prevalence of this logic means that when dealing with sustainability issues, the focus is partial and often ignores unwanted scaling effects such as the Jevons paradox (Giampietro and Mayumi, 2018) or unequal exchange (Hickel et al., 2022). This results, at best, in local socio-environmental improvements that overlook adverse systemic effects (Parrique et al., 2019).

The traditional separation between facts and values is no longer tenable. The economic context influences scientific institutions —where private, public, and military funding prioritises specific topics and methods over others (Oreskes, 2021)— and demands careful consideration of how these interests shape human curiosity and the pursuit of knowledge. Since underlying value systems and beliefs deeply influence scientific activity, analysing and clarifying these influences is essential (Echevarría, 1995). Regarding this matter, it is crucial to acknowledge that the socioenvironmental crisis is also an epistemic crisis (González-Márquez and Toledo, 2020), necessitating a critical examination of our mental models (Lent, 2018). This is why I invoke Schumpeter's concept of fundamental vision as the "preanalytic cognitive act" in this chapter, advocating for an explicit account of ontological presuppositions (Schumpeter, 1954). This task is about clearly identifying the basic assumptions about what constitutes the reality we engage with, its key features and the epistemic tools associated with this vision.

Neoclassical economics (i.e., conventional economics) is society's dominant economics school of thought (Common and Stagl, 2005). Therefore, it is essential to scrutinise its foundational claims. In this way, we can put the basis for discussing the terrible simplification incurred when the representation of the economic process misses the complex interactions of elements in ecosystems sustaining life and the dense web of relations between social and natural systems. Moreover, this analysis tackles the necessary critique of the limitations of resorting to a single metric of account (in this case, money) when dealing with sustainability issues. Finally, it allows the reader to gain perspective on what will come next, placing the MuSIASEM methodology within ecological economics, more specifically in the field of sociometabolic research (Haberl et al., 2019), and in opposition to conventional economics.

Ideas shape how we think and act in the world. For this reason, reflecting on the implications of the pre-analytical choice of narratives is essential. For example, the narrative of conventional economics may be protecting vested interests and core capitalist institutions (Pirgmaier and Steinberger, 2019). Moreover, the two paradigmatic theories conventional economics advocates —economic growth and price-making markets — contribute to legitimising policies that destroy ecosystems and life conditions (Spash, 2020a). According to Spash (2017), modern economics is a source of distraction from reality, and there is an urgent need to undermine its basic understanding and to provide alternative ones for new generations. Personally, I could not agree more. The rest of Chapter 2 is structured as follows: section 2.2 synthesises the fundamental vision of conventional economics and its standard procedures for addressing environmental issues. Section 2.3 describes the main problems associated with valuing nature in monetary terms, which are theoretical (section 2.3.1) and related to the multidimensionality of sustainability concerns (section 2.3.2). After identifying shortcomings, section 2.4 introduces the fundamental vision of ecological economics. Finally, section 2.5 summarises sociometabolic research as a paradigm for addressing environmental concerns faithful to ecological economics' founding principles (section 2.5.1) and synthesises the main approaches (section 2.5.2). The chapter closes with some conclusions in section 2.6.

2.2. The fundamental vision in conventional economics.

Conventional economics (CE) portrays the human economy as a closed, isolated system from its natural environment. That is, it envisions the economy as a self-contained entity and the economic process as a circular flow with no interaction with its environment. This point of view reduces the economic process to a mere circulation of monetary flows, products, and production factors. However, this simplification overlooks ecological processes' crucial role and limits our understanding of the complex interactions between the economy and the environment (Giampietro, 2019).

According to this circular vision, the economy has two parts in the classic diagram with which introductory economics texts begin (Figure 2.1): the production units (i.e. firms) and the consuming units (i.e. households). Firms produce and supply goods and services to households. Households demand goods and services from firms. Firm supply and household demand are met in the goods market, and prices are determined by the interaction between supply and demand (upper part). At the same time, firms demand factors of production from the households, and households supply factors to the firms. Prices of factors (land, labour and capital) are determined by supply and demand in the factors market (lower part). These factors' prices, multiplied by the amount of each factor owned by each household, determine the income of each household. The sum of all household incomes determines the National Income. Likewise, the sum of all goods and services produced by firms for households, multiplied by the price at which each is sold in the goods market, is equal to the National Product. By accounting convention, National Product must equal National Income (Daly and Farley, 2011). In this vision, nothing enters from outside the system, and nothing exists in the system outside. The object of economic science and the definition of social wealth is reduced to the study of the appropriable, exchangeable, producible, and valued in monetary terms goods and services. In turn, the representation of the economic process is focused on the self-sufficient universe of exchange values rather than being concerned with using physical matter and energy in the human economy[2] (Naredo, 2015).

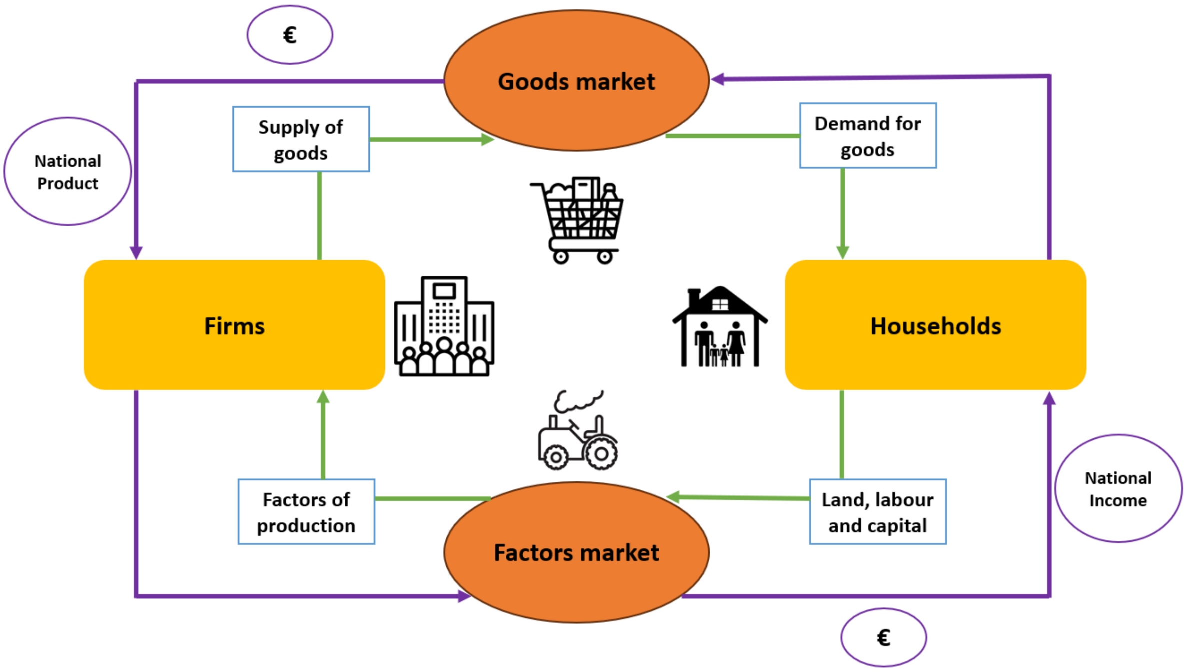

Figure 2.1. The circular flow diagram in CE. Adapted from Daly and Farley (2011).

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[2] Naredo (2015) traces the beginning of the process that ends with the focus on abstract exchange value in the post-physiocratic epistemological break. This break was gestated in the classical economic period and completed with the so-called marginalist revolution in the 1880s with the works of Jevons and Walras. Interested readers can deepen their knowledge about the evolution of economic thought by reading the monumental book *La Economía en evolución*.

This fundamental vision in CE is associated with various ontological assumptions when studying the functioning of economies. At the micro level (i.e. microeconomics), society is regarded as an aggregation of individual agents, each pursuing their self-interest as optimising machines, maximising utility based on a predetermined set of preferences, known as methodological individualism (Krugman and Wells, 2006). Drawing from a subjective theory of value, welfare depends on what people want, which they reveal through market transactions. The market system ensures efficient allocations in an economy of scarce resources[3] (Common and Stagl, 2005). However, this reasoning only reveals preferences for market goods. It implicitly assumes that not market goods (e.g. tangible natural resources such as solar energy or water or ecological services such as climate regulation or pollination) contribute little to welfare. As humans are assumed to be insatiable, welfare is increased through the growing provision of goods and services measured by their market values. Thus, the unending increase in the National Product (i.e. economic growth) is a considerate and adequate, measurable proxy of improvement (O'Neill, 2015). Furthermore, at the macro level (i.e. macroeconomics), there are only flows of goods and services between firms and households. Physical flows in one direction are matched by monetary flows in the other. Economic growth is merely how fast the flows occur, being able to continue forever as an exchange between production and consumption units.

Since the 1950s, CE has shown primary concerns about emissions and other polluting waste, thus cementing the development of environmental economics (Spash and Ryan, 2012). Environmental economics recognises that welfare also depends to a large extent on ecosystem services and suffers from pollution. As markets rarely exist for environmental issues, market allocations produce an inefficient result from the existence of externalities[4] (Rosas-Sánchez, 2023). Environmental economists use various techniques to assign market values to them so that they may be incorporated into the market model. The extension of markets can occur directly by constructing markets for environmental goods (e.g. tradable emissions permits). Alternatively, it can take place indirectly by calculating shadow prices, i.e. estimating the price that the

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[3] Generally, an allocation is efficient, or Pareto optimality, if there is no possible rearrangement of inputs to production, levels of production or share-outs of what is produced that could make somebody feel better off without making anybody feel worse off (Common and Stagl, 2005, p. 311).

[4] In economic theory, externalities are an important source of market failures. An externality occurs when an activity or transaction by some party causes an unintended loss or gain in welfare in another party, and no compensation for the change in welfare occurs (Daly and Farley, 2011). A typical example of a negative externality is water pollution by an upstream logging company that a downstream irrigation community must use.

environmental service, good or bad, would have if it were traded in competitive markets for cost-benefit analysis. This can be done basically by employing either preferences revealed in the market behaviour (e.g. the travel cost method) or stated preferences about hypothetical scenarios determined by the willingness to pay (or the willingness to accept compensation) in the level of the provision of a non-market good (e.g. contingent valuation) (Martinez-Alier and Roca-Jusmet, 2013). Environmental economists also adopt a “weak sustainability” perspective to address environmental problems. Resources are only scarce relative, not in absolute terms. Thus, the environment does not limit the economy’s expansion, making it possible to deal with situations of absolute scarcity because of the possibility of substituting natural capital for artificial capital, thanks to technological progress (Kerschner and O’Neill, 2015).

In sum, CE’s fundamental vision is associated with a narrative about the reality where narrow self-interest is the only dependable human motive, continued economic growth is feasible, technology will always solve human problems, and the market can efficiently allocate all types of goods, including environmental goods. This narrative is contested in the rest of this thesis. The following section addresses the problems that reveal the limits of market-based approaches to tackling environmental issues. However, a particularly relevant reflection in the framework of the thesis follows from this section. Sustainability is about preserving the capacity of the integrated economic-environment system (i.e. a social-ecological system, as we see in the next chapter) to meet human needs and desires over the long term (Common and Stagl, 2005). In that case, the fundamental vision of CE has no power of discrimination or anticipation concerning sustainability. It cannot provide any answer to the types of interactions that occur between the economy and the surrounding environment. Constructing a conceptual model around the individual act of consumption overlooks the physical and environmental context in which economic activities occur and fails to address the importance of shared socio-technical imaginaries that shape the social identity of an economy.

2.3. Monetary valuation in the context of sustainability: identifying concerns.

2.3.1. Theoretical concerns.

Markets use individual self-interest to efficiently allocate resources among alternative ends via the pricing mechanism (Krugman and Wells, 2006). However, markets function efficiently only with a limited range of goods. According to Daly and Farley (2011), the specific characteristics that goods must possess for the market mechanism to allocate them efficiently are excludability and rivalness. Excludability is a legal principle that, when enforced, allows an owner to prevent others from using a determined asset. It is virtually synonymous with property rights. Thus, an excludable good is one whose ownership allows the owner to use it while simultaneously denying others the privilege (e.g. when I use my bicycle, I can prohibit others from using it). Market production and allocation are dedicated to profits. If a good is not excludable, someone can use it regardless of whether any producer of the good allows it. So, there will not be profits from its production. In turn, rivalness is an inherent characteristic of certain goods whereby consumption or use by one person reduces the amount available for everyone else. A rival good is one whose use by one person precludes its use by another person (e.g. flood, clothing, cars, and homes are rival goods). If a good is nonrival, an additional person using the goods imposes no extra cost to society. Markets allocate goods sold for a price, and consumers pay the price to use these goods until the marginal benefit equals the price (i.e., the marginal cost). A price, by definition, is more significant than zero. However, the marginal cost of additional use of nonrival goods is zero.

What is relevant here is that many of the goods and services provided by nature have physical characteristics that make it almost impossible to design institutions that would make them excludable. There is no conceivable way that an individual can own climate stability, atmospheric gas regulation or protection from UV radiation since no viable institution or technology could allow one person to deny all others access. Moreover, most environmental goods are nonrival resources since their use by one person does not affect their use by another (e.g. if I use the ozone layer to protect me from skin cancer, there is just as much left for others to use for the same purpose). Therefore, markets will not lead to the efficient allocation of goods that cannot be owned and for which use does not lead to depletion, i.e. the bulk of ecosystem services (Daly and Farley, 2011). Except for some limited goods and services (rival and excludable ones), monetary fetishism, according to which everything must be translated into monetary values and the scope of markets must be extended, is an unsatisfactory claim from the scientific point of view due to the intrinsic characteristics of many environmental goods and services (Martinez-Alier and Roca-Jusmet, 2013). Moreover, this option may be counterproductive for ecological conservation (Pascual et al., 2023).

Similarly, Giampietro et al. (2012) stress that using exchange values (i.e., prices) to assess the value of special and unique entities is inconsistent with economic theory.

The Walrasian model is based on the assumptions of moderate scarcity and complete substitution among the various items in the utility function. Thanks to a techno-optimistic perspective based on a weak sustainability perspective, human ingenuity will reestablish a moderate scarcity when the price of some needed goods or services rises too high. However, this vision conflicts with the definition of sustainability issues, which include elements or resources essential for the survival of ecosystems or human societies or for which there are no adequate substitutes or equivalents. When something is unique, it becomes invaluable in terms of exchange value. It has an existing value that cannot be captured in the market. For example, coal and petrol are not merely items with subjective value and, consequently, exchange value; they represent a specific quantity of stored energy that imposes strict and calculable limits on modern industrial and consumption activities with, at present, no substitutes in sight. However, the valuations from the markets make us consume them incorrectly as if these resources came from an inexhaustible source. Therefore, the ability of market prices to quantify exchange values refers only to goods and services with some type of equivalent.

Additionally, placing a price on everything within ecosystems requires information and calculation abilities far beyond human capabilities (Daly, 2019). For instance, let us consider the calculations needed to quantify and internalise the costs associated with global warming accurately. Given the complex relationship and significant uncertainty involved (e.g. global warming leading to positive feedback loops, such as the release of methane from arctic tundra or the increase in atmospheric water vapour from more rapid ocean evaporation —both potent greenhouse gases— or negative feedback loops via increased carbon sequestration by forest), translating these costs into monetary units is clearly beyond the capabilities of modern science. In this sense, the compression of the complex, interconnected processes in nature into simple metrics results in arbitrary and partial monetary valuations (Naredo, 2019) or “formalism nonsense” (Giampietro et al., 2012).

Considering all these factors, we can conclude that the market’s invisible hand doesn’t work concerning “nonmarket goods”, leading to inefficient outcomes. Moreover, even more critically, achieving allocation efficiency does not guarantee sustainability (Common and Stagl, 2005). In CE, if anything has value, it is what people are willing to pay for. The preferences of individuals determine economic performance. Thus, if no one has a strong preference for the conservation of a species or the correction of a certain level of contamination with implications for sustainability, they can be ignored based on the efficiency criterion. Making room for the prosperity of other species and the proper functioning of the ecological life support system is beyond the scope of CE.

2.3.2. Other concerns.

Along with theoretical concerns, the unidimensional focus on monetary valuation raises issues related to intergenerational, plural values, alternative institutional settings, and financial considerations. The following lines will address each of these issues.

(i) Intergenerational concerns. As socialists have long noted (Harvey, 2010), within any generation, the social well-being of individuals who lack monetary means disappears from social choices. Additionally, the well-being of future generations who are necessarily absent from current markets cannot be directly captured in market exchange (Martinez-Alier and Roca-Jusmet, 2013). For a market to function optimally, everyone who wants to produce or consume the goods being marketed must be able to participate. However, this condition encounters one ontological difficulty: future generations cannot participate in today's markets, and therefore, today's market prices do not reflect their preferences. The market can "efficiently" allocate resources only if we assume that future generations can be ignored entirely. Consequently, CE cannot deal with the intergenerational allocation of exhaustible resources and pollution, even if they are valued in markets, because non-born agents cannot bid in today's markets. Prices are usually corrected by applying a discount rate to consider the subjective ethical opportunity costs of present utilisation, which sacrifices future utilisation. In this way, questions on the optimality of the inter-generational allocation of environmental goods cannot be separated from moral values associated with the weight (a higher discount rate implies a more significant present undervaluation of the future) given to the demands of future generations (Martinez-Alier, 1987). The mainstream discourse avoids facing the issues of ethical attitudes towards future generations. With economic growth, the future is considered to be more prosperous than the present, and therefore, the marginal utility of consumption is lower than it is today. It also allows for social consensus without laying inequality between classes and countries on the table (Common and Stagl, 2005).

(ii) Incommensurability concerns. An important argument is whether money's measuring rod can capture all the value dimensions in sustainability analysis. The view that rational decision-making requires a single measure of the value of the different options has its basis in the utilitarian background of welfare economics, where well-being is directly brought under the measuring of money. Given this assumption, rational choices about the environment require the extension of the measuring rod of money to include preferences for environmental goods which are unpriced in actual markets (O'Neill, 2017). Against monetary commensurability, Raz (1986) appeals to constitute incommensurability. Certain relationships and commitments (e.g. love, friendship, well-being) are formed by the refusal to be treated as tradable commodities that can be bought or sold. Graeber (2013) argues that we speak of value when labour is commoditised. The moment we exit the world of labour relations, we begin talking about "values". The value of "values" lies precisely in their lack of equivalence. They are felt as unique by specific individuals, and because of that, they cannot or should not be converted into money. In this sense, the environment is a site of competing values and interests that are not reducible to each other or to some other ultimate value (Martinez-Alier et al., 1998). Giampietro (2018) contends that sustainability, as a complex problem, entails dealing with social and technical incommensurability. Social incommensurability implies the existence of non-equivalent perceptions associated with contrasting and legitimate values of what is relevant and desirable. Technical incommensurability is related to the impossibility of reducing the various useful representations of a complex phenomenon into a single quantitative model. Incommensurability does not mean that things are not measurable. Social incommensurability means that different values associated with different feelings, perceptions, or aspirations cannot be compared or weighted against a given "objective" standard. Technical incommensurability means that the representations referring to non-equivalent descriptive domains (e.g. different scales and dimensions of analysis) cannot be reduced into a single coherent quantitative model. To rephrase, incommensurability entails rejecting both monetary and physical reductionism (e.g. eco-energy valuation) when informing policy (Martinez-Alier et al., 1998). Still, it allows various options to be comparable without recourse to a single value type (O'Neill and Uebel, 2015).

(iii) Institutional concerns. Valuation processes cannot be isolated from specific institutional frameworks (Vatn, 2005). Markets and monetary valuations from which a pattern of prices and quantities emerges result from specific social valuations (Martinez-Alier, 1987). For instance, in the case of agribusiness, in the current institutional framework, the environmental costs and the effects of overexploitation of cheap labour are not reflected in the price paid for foodstuffs (Ecologistas en Acción, 2024). On this matter, how nature is predominantly valued follows directly from the general characteristics of capitalist society (Kallis et al., 2013). Capitalism centres at its heart on the accumulation of economic surplus on an extended scale fuelled by the systemic need to accrue profits and survive under competition (Pirgmaier and Steinberger, 2019). Therefore, the structural condition of capital accumulation generates a specific valuation framework where nature is valued when it can be marketed and sold and profits made from it. However, it is worthless (if not negatively valued) when it is useless for capital accumulation or obstructs profit rates. Naredo (2010) points out that the valuation processes in the capitalist framework follow what he calls the "notary rule". According to this rule, there is a growing asymmetry between the monetary value and the physical cost; that is to say, the greater the physical cost and the painful work, the less the monetary valuation. Thus, much of the physical costs of production processes are ignored or valued at a residual price and waste generation is not penalised. In the same vein, Foster et al. (2010) argue that increases in exchanges, monetisation, and commodification under the laws of motion of the capitalist mode of production are central to understanding the ecological crisis. Capitalism expansion has produced dramatic spatial and environmental consequences, generating uneven geographical development under the control of the dominant class and corporate power (Harvey, 2006). In sum, institutional considerations involve issues of political power and cost-shifting processes affecting price formation. Additionally, they reveal the alliances between CE and capitalist institutions and the necessity to move beyond data-based empiricism to understand underlying structures and social relationships (Spash, 2020a).

(iv) Financial concerns. The accounting of monetary flows is losing its ability to monitor the aggregate size of biophysical processes underlying actual market transactions (Giampietro et al., 2012). The concept of "added value" refers to a physical process in which something is produced, an economic activity with associated biophysical costs. However, as Naredo (2019) argues, the economy's financialisation has led to decoupling the value of the money supply, financial assets, and derivatives from the GDP. This dramatic increase in the circulation of virtual money makes it extremely difficult to assess, let alone control, the quantity of money in circulation (Mayumi and Renner, 2023). Thus, money has lost its capacity to reflect measurable attributes associated with external references in the biophysical world. This dissociation between monetary and physical variables resonates in the already classic work of Soddy from the early 20th century (Soddy, 1926). He compared "real wealth", which grows at the pace of natural processes and is worn down when converted into manufactured capital, with "virtual wealth" in the form of debts that apparently could grow forever. Financial capital was supposed to grow independently at compound interest, ad infinitum. While this belief is a convention within human society (produced within a determined institutional framework), it cannot persist indefinitely in the face of the biophysical reality governed by the principles of thermodynamics.

All the shortcomings mentioned in this section and the previous ones reveal the limits of market-based approaches to sustainability analysis. At this point, Kapp's (1974) claim that environmental values are social use values for which markets provide neither a direct measure nor an adequate indirect indicator resonates powerfully. A contrasting vision and analytical tools are needed to understand society-nature interactions better and generate effective proposals to reverse environmental degradation. The following section introduces ecological economics.

2.4. The fundamental vision in ecological economics.

Ecological economics[5] (EE) has emerged as a response to the pressing "modern environmental crisis", a crisis that traditional economic approaches have been unable to address (Pirgmaier and Steinberger, 2019; Røpke, 2004). The fundamental vision of EE is that the economic system is a part or subsystem of the larger global ecosystem that sustains it (Figure 2.2).

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[5] Despite some intellectual origins in the XIX century that the interested reader can track in the work of Martinez-Alier (1987), EE was institutionalised with the establishment of the International Society of Ecological Economics (ISEE) in 1988 and the journal *Ecological Economics* (first issue 1989) (Røpke, 2004)

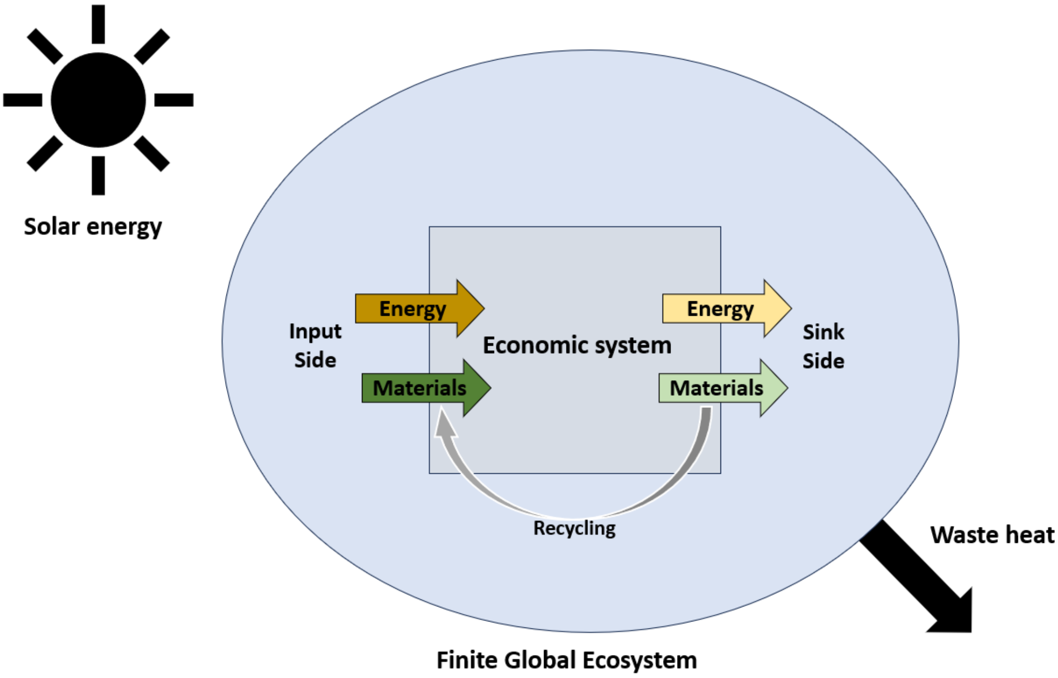

Figure 2.2. The fundamental vision in EE. Adapted from Goodland et al. (1993).

EE offers a “Copernican” view in which the economic system is part of a larger, enveloping, and sustaining whole: the Earth, its atmosphere, and its ecosystems. This more extensive system is finite, nongrowing, and materially closed, although open to solar energy. The human economy is an open system inside a closed system in the thermodynamic sense[6] (Arenas et al., 2022). The human economy exchanges matter and energy with the larger system of Earth. In contrast, the Earth does not exchange matter with the surrounding universe (except for a few meteors or space debris such as inoperative satellites or rocket stages). The Earth receives solar energy from outside and emits heat, and this energy flow keeps up the processes of the whole system. What this fundamental view stresses (and has been abstracted from the CE’ circular model) is the linear throughput of matter and energy by which the economy is supported by its environment. This linear throughput is the flow of raw materials and energy from the global ecosystem’s sources (e.g. mines, wells, fisheries, croplands) through the economy and back to the global ecosystem’s sinks in the form of different kinds of wastes. This linear flow is critical to the need to acknowledge the existence of biophysical limits. There are finite supplies of energy, raw materials, finite absorption capacities and poorly understood but also finite capacities for ecosystems to provide life support

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[6] In thermodynamics, an open system exchanges both energy and matter with its surroundings, like a boiling pot of water. A closed system, such as a sealed container, allows energy exchange but not matter. An isolated system exchanges neither energy nor matter, representing an ideal case like the universe or a perfect insulated thermos.

functions (Daly and Farley, 2011). The human economy can take up more or less “space” in the biosphere and accelerate or slow down the pace of the metabolised flows to guarantee its maintenance, reproduction and adaptation (Giampietro, 2023). In this way, it can determine changes in the scale of the economy. The larger the scale of the economy, the greater the risk of destroying the conditions for human life on Earth in the long run (Daly, 2005).

Considering this vision, the economic process is not a mechanical analogy that can be run forward and back, nor a circular process that can return to any previous state, as the circular flow of Figure 2.1 suggests. Instead, it is an irreversible and irrevocable process moving toward time’s arrow of increasing entropy (Georgescu-Roegen, 1971). Every loop around the circular rent flow creates dissipation, attributed to losses in quantity (i.e. physical material losses, by-products) and quality (i.e. mixing, downgrading, and dispersing). To overcome these dissipation losses, new materials and energy must be injected. As commodity production increases, more energy is dissipated in the form of pollution, which will be impossible to reuse in the next cycle (Giampietro, 2019). In the economic process, laws that govern physics, especially the laws of thermodynamics, are relevant. The First Law of Thermodynamics indicates that we cannot make something from nothing; hence, all human production must be ultimately based on natural resources. These resources are transformed through production processes into something of use for humans, and transformation requires work. In turn, only the availability of fluxes of negative entropy coming from the environment (determining the availability of free energy) can provide work. The Second Law of Thermodynamics, also known as the Entropy Law, emphasises that resources transformed into something useful (to be used inside the economy) inevitably disintegrate or decay into less useless forms after use, generating a steady flow of waste into the environment. This law highlights that production processes convert matter and energy forms (primary flows on the supply side) into useful materials and energy carriers (secondary flows) that can be used for economic purposes. The subsequent use transforms these secondary flows into waste and useless energy forms that have to be absorbed by the context (primary flows on the sink side) (Common and Stagl, 2005). However, as a system of provision, the economy cannot be reduced to purely physical or entropic terms. The entropic process moves through an intricate web of anthropomorphic categories of utility and labour, and the value of production derives from the satisfaction of human needs and wants (Burkett, 2006).

The implications of the economy's embeddedness in nature and nature's importance as a life support system make EE's ontological grounds incompatible with CE (Spash, 2015). At the micro level of individuals, objective aspects of reality, such as the satisfaction of basic needs, become evident. Irreducibility of needs and incommensurability of values are two critical pillars of EE. In opposition to CE, where compensation and substitution are essential elements, EE considers that some goods are more important (e.g. before enjoying a convertible, I need to cover my food needs to stay alive) and cannot be substituted by other goods, i.e. what economists call a "lexicographic" order of preferences. In part, due to this "lexicographic" order, there are limits to the degree of substitution between different types of values (economic and non-economic) (Martinez-Alier and Muradian, 2015). Moreover, how nature and society are interrelated raises issues of environmental ethics, recognition of the non-human world and concern for fair and equitable treatment of future generations that go beyond the egoist utilitarian framework based on preferences (Spash, 2020b). At the macro level of the whole economy, social provision is core to the economic problem, and addressing it requires the inclusion of the structural constraints imposed by biophysical reality in contrast to the EC's position on social provisioning based upon the price-making market paradigm (Spash, 2020a). Pollution and waste are inevitable parts of the economic process, not avoidable externalities that disappear if the prices are "right". These adverse effects are, therefore, seen as pervasive social and environmental costs, not correctable market failures (Kapp, 1978). In turn, the foundational critiques of economic growth, based on physics as advanced by Georgescu-Roegen (1971), oppose macroeconomic growth. There must be limits to economic growth related to resource depletion (input side) or waste absorption (sink side) (Arenas et al., 2022).

To offer a methodological toolkit for studying social-ecological complexities in realistic and transformative ways (Pirgmaier and Steinberger, 2019), EE's analytical tools are not committed to a unique type of value expressed in a single unit of account and encompass monetary valuation and physical appraisal of the environmental impacts of the human economy measured in different units (Gerber and Scheidel, 2018). In EE, the sustainable scale replaces growth as a goal. The scale of the human subsystem has a size where the throughput by which the ecosystems maintain and replenish the economy is ecologically sustainable (Daly, 1977). To achieve this sustainable scale, two separate sets of indicators are required (O'Neill, 2015): (i) a set of biophysical indicators to measure how society's level of resource use is changing over time and whether this level of resource use is within ecological limits; and (ii) a set of social indicators to measure whether people quality of life is improving. So, there is a set of multidimensional indicators instead of single indicators based on monetary valuations.

In short, EE was institutionalised at the end of the 1980s with the goal of understanding the economy within its biophysical limits while acknowledging the necessity for human society to respect the rights and well-being of all, both present and future, including both human and non-human entities. EE supports anti-establishment concerns for limits to material and energy throughput and restricting the scale of the economy (Røpke, 2004). However, different forces have shaped how this field of knowledge has combined topics and addressed these various issues (Røpke, 2005). In particular, society's gradual but persistent neoliberalisation since the 1980s has pushed the environmental policy discourse into the language of CE and finance (Gómez-Baggethun and Naredo, 2015). The result has been the mainstreaming of environmentalism in general and EE in particular (Spash, 2012). EE has been losing its original heterodox roots and is increasingly encroaching on purely market-based approaches (Gerber and Scheidel, 2018), where the valuation of ecosystem services is becoming central in EE (Plumecocq, 2014). The field is disunited and internally self-contradictory (Spash, 2020b). For this reason, different researchers consider that the concept of social metabolism allows building an economic-ecological field of study faithful to the founding principles of the EE (Fischer-Kowalski, 1998; Giampietro et al., 2012; González de Molina et al., 2019; González de Molina and Toledo, 2014; Infante Amate et al., 2017; Plumecocq, 2014). Concerning this concept and sociometabolic research, I will dedicate a few lines in the next section.

2.5. Sociometabolic research.

2.5.1. Definition and main principles.

The concept of "social metabolism" grew from the observation that biological systems (e.g. organisms, ecosystems) and socioeconomic systems (e.g. households, firms, economies) decisively depend on a continuous throughput of energy and materials to maintain their internal structure. More specifically, "social metabolism" refers to the need to stabilise an expected set of energy and material transformations occurring within an open social system, such as an economy, and between this system and its environment. These complex processes of transformation determine the functional structure of the system, ensure its reproduction, maintain and repair its parts, and present specific dynamics, allowing for adaptation in changing contexts (Giampietro et al., 2012).

Attempts to integrate economic analysis with biophysical analysis to improve our understanding of the functioning and evolution of human society have a long history (Fischer-Kowalski, 1998; Martinez-Alier, 1987). The concept of "metabolism" arose in the early nineteenth century, particularly concerning the body's material exchanges for respiration. Later, it extended to include material exchanges between organisms and the environment and the bio-physical processes within the living entities (Swyngedouw, 2006). For example, in the writings of Jacob Moleschott (1857) and Justus von Liebig (1840), metabolism denoted the exchange of energy and substances between an organism and the environment and the totality of biochemical reactions in a living thing.

In social theory, the concept of metabolism was introduced in an ontological and epistemological framework in the early Marxist formulations of historical materialism as a central metaphor for Marx's definition of labour and for analysing the relationship between humans and nature. "Labour is, first of all, a process between man and nature, a process by which man, through his own actions, mediates, regulates, and controls the metabolism between himself and nature." (Marx (1867), in Swyngedouw, 2006, p.26). In this view, the environmental "production" process is conceived in the broadest possible sense. It refers to the metabolic process energised through the fusion of humans' physical properties and creative capacities with those of non-humans. Each mode of production creates a particular social metabolic order that determines the interchange between society and nature. Such interactions influence the ongoing reproduction of society and ecosystems (Foster et al., 2010).

From the initial contribution of Marx, the concept of society's metabolism provides a valuable understanding of the interrelation of society with nature. Among the authors from the social and natural sciences who played a pioneering role in the development of this field, we ought to mention Geddes (1884), Jevons (1865), Podolinsky (1883), Ostwald (1912, 1909), Soddy (1926, 1912), Vernadsky (1926), Lotka (1925, 1922), White (1943), Cottrell (1955) and Steward (1968) —see a historical review in Fischer-Kowalski (1998) and Fischer-Kowalski and Hüttler (1998).

Toledo (2008) argues that social metabolism offers an analytical framework for understanding human appropriation of nature. In this sense, human beings' relations with nature are always twofold: individual and collective. At the individual level, humans extract sufficient amounts of oxygen, water, and biomass from nature per unit of time to survive as organisms while excreting heat, water, carbon dioxide, and mineralised and organic substances. At the social level, individuals organise through various types of relationships or connections to ensure their survival and reproduction. They also extract energy and materials through artefacts operated under human control and excrete a wide range of waste (e.g. plastic, nuclear waste or greenhouse emissions). These two levels correspond to what the biologist and system ecologist Alfred Lotka (1922) introduced as the distinction between endosomatic and the exosomatic use of energy[7] by humans, a distinction with founding value for EE (Martinez-Alier and Roca-Jusmet, 2013).

Social metabolism has been used as a theoretical framework for understanding socio-environmental change (González de Molina and Toledo, 2014; Haberl et al., 2016) or as a set of methodological tools for analysing the biophysical dynamics of the economies (Fischer-Kowalski and Weisz, 2016; Krausmann et al., 2009; Wiedmann et al., 2015). In all its forms, social metabolism provides a perspective for exploring the relationship between society and nature by examining its material foundations, primarily through the study of energy and material flows (González de Molina and Toledo, 2014). Explicitly or implicitly, sociometabolic research (SMR) builds on the following assumptions (Haberl et al., 2019):

(i) The functioning of social systems, including the economy, depends on effectively organising energy and material flows to expand, maintain, and operate their biophysical basis, which includes the human population, livestock, and artefacts. This biophysical basis generates significant outputs, such as physical, intellectual, or emotional labour, as well as products like bread, clothes, or electricity, and services such as living space or mobility.

(ii) The composition, magnitude and patterns of social metabolism determine society’s environmental pressures and impacts. Sustainability requires sociometabolic flows to be compatible with the biosphere’s capacity to supply resources and absorb waste.

(iii) Important principles of the natural sciences, such as the laws of thermodynamics, apply to the metabolism of socio-economic systems and are fundamental for their understanding.

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[7] Endosomatic energy is the energy use by an organism internally to maintain its functions, while exosomatic energy comes from external sources, like technology, to support activities outside the body. This distinction helps to explain how energy is managed and utilised by organisms and societies.

After a slight decline in the 1990s, the turn of the millennium, and growing societal concerns about climate change, peak oil, material shortage, and the impacts of current industrial metabolism on human health and ecosystems, the topic of the interaction between society and nature has gained prominence (Giampietro et al., 2012). A critical bibliographical analysis found that references to "social metabolism" rose from 400 in 1991-2000 to over 3 000 in the following decade and another 6 000 in 2011-2015 (Infante Amate et al., 2017).

2.5.2. Methodological approaches within SMR.

SMR has become a paradigm for addressing current environmental concerns as a multidimensional problem (Haberl et al., 2021). It goes beyond the conventional eco-efficiency analysis, such as the ratio of GDP to resource use (UNEP, 2011), by providing a richer and more comprehensive picture. SMR also offers valuable insights for interdisciplinary analyses of (un) sustainable society-nature interactions, for example, by highlighting the relationships between different resources (e.g., land, water, and energy) (MAGIC Consortium, 2020).

Gerber and Scheidel (2018) consider MuSIASEM and MEFA today's two major sociometabolic approaches to the substantive (i.e., in substance) study of economic processes. These two methodologies not only focus on a specific resource use but also aim to understand the biophysical scale and dimensions of the economy as a whole and in relation to other economic and ecological processes:

(i) Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MUSIASEM) (Giampietro and Mayumi, 2000a, 2000b) views metabolism as determined by a phenomenon of group autocatalysis. This perspective entails that the particular identity of the system defines across different levels of analysis the set of energy forms that have to be produced and consumed (secondary flows metabolised inside the system) and the primary flows that must be available in the form of supply and sink capacity form the environment. This methodology uses a flow-fund model (Georgescu-Roegen, 1971) to characterise societal and ecosystem metabolism.

(ii) Material and Energy Flow Analysis (MEFA) (Fischer-Kowalski and Weisz, 2016; Haberl et al., 2016) focuses on analysing the throughputs of various forms of energy and matter within society. However, it does not specify the criteria for selecting which material and energy forms should be included in the analysis in relation to the society's identity. This approach differentiates between stocks and flows in its representation of the metabolism.

Other approaches are material and substance flow analyses (Ayres and Kneese, 1969; Baccini and Brunner, 2012), input-output analyses (Leontief, 1986; Wiedmann et al., 2007); and life-cycle analyses (Bjørn et al., 2020; European Union Joint Research Center, 2010). Another noteworthy line of inquiry is provided by the work of Vaclac Smil (2015, 2008), which can be termed "societal energetics". This approach uses technical aspects of the set of energy conversions within society to evaluate the feasibility and viability of future scenarios and, in this way, assess the quality of potential alternative energy sources. Other specialised instruments in the sociometabolic toolkit include the Energy Returned on Energy Invested (EROI) proposed by Charlie Hall (Hall and Klitgaard, 2018), the calculus of the virtual water, conceptually introduced by John Anthony Allan (Allan, 1997) and expanded by Arjen Y. Hoekstra (Hoekstra and Mekonnen, 2012), the controversial ecological footprint (Giampietro and Saltelli, 2014; van den Bergh and Grazi, 2014) introduced by Mathis Wackernagel and William Rees (Rees and Wackernagel, 1996), and various "hybrid" approaches (Pauliuk et al., 2015). Some overlaps may exist between these methods, and the differences mainly lie in their purpose, scope and data requirements.

González de Molina and Toledo (2014) observe that an analysis of the current metabolism studies reveals two key issues. First, much of the literature focuses solely on material interactions between human societies and nature, treating the concept of social metabolism merely as a methodological tool or a new form of environmental accountancy. This issue has led to a proliferation of multiple interpretations and a lack of a cohesive theoretical framework, as seen with various footprint indicators (Matuštík and Kočí, 2021). Second, there is a notable absence of an in-depth consideration of the social dimension —encompassing cultural and political aspects— that many social metabolism studies overlook, such as input-output analyses (Miller and Blair, 2009). The *societal metabolism* framework of MuSIASEM, which I will explain in detail in the next chapter, addresses these limitations and provides a range of analytical tools for examining the material basis of human societies.

2.6. Conclusions.

CE assumes a conceptual framework in which factors of production (i.e. land, capital and labour) are transformed without loss or friction into goods ready to be sold. This vision feeds a circular and self-sufficient system where all produced goods are consumed, focusing narrowly on exchange within price-making markets. However, a clear knowledge gap exists in how the economic process is represented. It fails to account for the contribution of environmental goods and services to production and neglects the inevitable waste and pollution generated in any production and consumption process. Thus, a distorted perspective is produced where ecological deterioration becomes invisible, legitimising social policies and practices that promote environmental unsustainability and encourage consumerism.

From a human perspective, the functioning of the ecosystem is decisive because of the supply of natural resources, assimilation capacity, and supply of a variety of ecological services. However, under the conceptual framework of CE, we cannot map the relationships between human and natural systems. There are no explicitly society-nature interactions. Balances or indicators of the natural environment change due to human processes are not integrated into their analysis. Thus, it is assumed that the amount of energy and materials available to produce goods and services is the same after each productive cycle (i.e. each turn of the circular flow of income) and reaffirms the possibility of growing indefinitely in a finite world. In short, it is not possible to study the sustainability of the joint economic-environment system. Besides, given the characteristics of most environmental goods and services (i.e. not excludable and nonrival), they resist monetary valuation and integration into market mechanisms. Ecological systems are neither observable nor controllable through market prices, and CE's policies and instruments are generally inadequate in addressing environmental problems. Finally, value monism —extending the measuring rod of money to all aspects of reality— raises intergenerational, incommensurability, institutional and financial concerns.

Opposite the CE, EE offers a radically different mental model of reality (see Table 2.1). The discipline's original aim was to challenge and transform society and the economy rather than merely pursue the mainstream economic goals of efficiency and growth. EE also aims to contribute to a progressive social-ecological understanding of the world, which can provide well-founded alternative policy recommendations. Over time, EE has become transdisciplinary within the broader framework of sustainability science and management (Costanza, 1991). Although the rise of pragmatism in the field has tempered some of its radical original aspects —particularly with the excessive prominence of ecosystem service valuation (Plumecocq, 2014)— sociometabolic approaches and degrowth perspectives have remained influential. Moreover, there is a growing momentum among scientists, citizens and policymakers for approaches advocating an urgent transition to a post-growth economy (Generation Climate Europe, 2023).

Table 2.1. Conceptual models in CE and EE.

Elements of reality	***Conventional Economics (CE)***	***Ecological Economics (EE)***
Human economy	It is considered the whole. When the environment is considered, it is often viewed merely as one sector within the economy.	The human economy is a part or subsystem of the larger global ecosystem that sustains it. This broader system is finite, nongrowing, and materially closed, although open to solar energy.
Economic process	It is viewed as a circular flow, a self-sustaining merry-go-round between production and consumption.	It is a linear process that involves extracting and dumping primary flows in the environment to satisfy human needs.
Individuals	They are assumed to be insatiable, optimising machines and maximising utility based on a preordained set of preferences. Welfare is increased through the ever provision of goods and services.	Objective aspects of reality, including the satisfaction of basic needs, determine the existence of a "lexicographic" order of preferences. Moreover, aspirations more relevant to human existence than mere selfishness, shaped by moral and environmental values, are also present.
Economic growth	Unending economic growth is typically considered an adequate, measurable proxy for improvement in well-being. Additionally, the environment is not seen as a constraint on economic expansion due to possibilities for substitution and technological progress.	Unlimited economic growth is physically impossible because the environment's supply and sink capacity are limited in absolute terms. Therefore, the scale of the economy must be controlled.
Environmental problems	As markets rarely exist in ecosystem services or pollution, various techniques exist to assign market values to them so that they may be incorporated into the market model. Environmental problems are externalities that can be corrected with minimal interventions.	Pollution and waste are seen as pervasive social and environmental costs, not correctable market failures. Market prices do not indicate whether a system is approaching its resilience limits. A multidimensional set of indicators (especially biophysical ones) is necessary to characterise biophysical limits and achieve a good life within planetary boundaries.

The paradigm of social metabolism provides a theoretical and analytical framework faithful to the original foundations of EE. It offers a perspective for analysing the relationship between society and nature through its material foundations, primarily by studying the flows of energy and materials. A critical approach within this paradigm is the Multi-Scale Analysis of Societal and Ecosystem Metabolism (MuSIASEM). This methodology, as we will explore in the next chapter, is grounded in a rich theoretical framework and provides valuable analytical tools for assessing the sustainability of human societies.

2.7. Chapter references.

Allan, J.A., 1997. “Virtual water”: a long term solution for water short Middle Eastern economies? (Vol. 5145). School of Oriental and African Studies, University of London, London.

Arenas, L., Naredo, J.M., Riechmann, J., 2022. Bioeconomía para el siglo XXI. Actualidad de Nicholas Georgescu-Roegen. Los Libros de la Catarata, Madrid.

Ayres, R.U., Kneese, A., 1969. Production, consumption and externalities. Am. Econ. Rev. 59, 282–297.

Baccini, P., Brunner, P., 2012. The Metabolism of the Anthropocene, 2nd edition. MIT Press, Cambridge.

Bjørn, A., Chandrakumar, C., Boulay, A.M., Doka, G., Fang, K., Gondran, N., Hauschild, M.Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., Ryberg, M., 2020. Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. Environ. Res. Lett. 15, 083001. https://doi.org/10.1088/1748-9326/AB89D7

Burkett, P., 2006. Marxism and Ecological Economics. Toward a Red and Green Political Economy. Haymarket Books, Chicago.

Chancel, L., 2022. Desigualdades Insostenibles: Por una justicia social y ecológica. Fuhem Ecosocial y Libros de la Catarata, Madrid.

Common, M., Stagl, S., 2005. Ecological Economics. An Introduction. Cambridge University Press, Cambridge.

Costanza, R., 1991. Ecological Economics: The Science and Management of Sustainability. Columbia University Press, New York.

Cottrell, W.F., 1955. Energy and Society: The relation between Energy, Social Change, and Economic Development. McGraw-Hill, New York.

Daly, H., 2019. Growthism: its ecological, economic and ethical limits. Real-World Econ. Rev. 87, 9-22.

Daly, H., 2005. Economics in a full world. Sci. Am. 293, 78–85.

Daly, H., 1977. Steady State Economy. Freeman, San Francisco.

Daly, H., Farley, J., 2011. Ecological economics : principles and applications (2nd edition).

Island Press, Washington.

Ecologistas en Acción, 2024. El verdadero precio de los alimentos. La cara oculta de la agroindustria en la península ibérica. Territorios de sacrificio: Mar Menor, L'Albufera, Doñana y Almería. Madrid.

European Union Joint Research Center, 2010. International Reference Life Cycle Data System (ILCD) Handbook-General Guide for Life Cycle Assessment. European Union, Luxemburg.

Fischer-Kowalski, M., 1998. Society's Metabolism: The Intellectual History of Material Flow Analysis, Part 1, 1860-1970. J. Ind. Ecol. 2, 61–78. https://doi.org/10.1162/jiec.1998.2.1.61

Fischer-Kowalski, M., Hüttler, W., 1998. Society's Metabolism: The Intellectual History of Materials Flow Analysis, Part II, 1970-1998. J. Ind. Ecol. 2, 107–136. https://doi.org/10.1162/JIEC.1998.2.4.107

Fischer-Kowalski, M., Weisz, H., 2016. The Archipelago of Social Ecology and the Island of the Vienna School, in: Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), Social Ecology. Springer International Publishing, Cham, pp. 3–28.

Foster, J.B., Clark, B., York, R., 2010. The Ecological Rift: Capitalism's War on the Earth. Monthly Review Press, New York.

Geddes, P., 1884. Civics as applied sociology (1979). Leicester University Press, Leicester.

Generation Climate Europe, 2023. Manifesto for an intergenerationally just post-growth European economy [WWW Document]. https://gceurope.org/wp-content/uploads/2023/07/Manifesto-for-a-post-growth-economy.pdf (accessed 16 August 2024)

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Gerber, J.F., Scheidel, A., 2018. In Search of Substantive Economics: Comparing Today's Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM. Ecol. Econ. 144, 186–194. https://doi.org/10.1016/j.ecolecon.2017.08.012

Giampietro, M., 2024. Combining biosemiotics and post-normal science to study the formation and adaptation of the identity of modern society. Futures 161, 103414. https://doi.org/10.1016/J.FUTURES.2024.103414

Giampietro, M., 2023. Metabolic flow, in: Padilla-Rosa, E., Ramos-Martín, J. (Eds.), Elgar Encyclopedia of Ecological Economics. Edward Elgar Publishing, Cheltenham, pp. 368–375.

Giampietro, M., 2019. On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. Ecol. Econ. 162, 143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001.

Giampietro, M., 2018. Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10, 1–17. https://doi.org/10.3390/su10072545

Giampietro, M., Mayumi, K., 2018. Unravelling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026

Giampietro, M., Mayumi, K., 2000a. Multiple-scale integrated assessment of societal metabolism: introducing the approach. Popul. Environ. 22, 109–153. https://doi.org/10.1023/A:1026691623300

Giampietro, M., Mayumi, K., 2000b. Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. Popul. Environ. 22, 155–210. https://doi.org/10.1023/A:1026643707370

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Societies : Where Economists Fall Short. Routledge, London.

Giampietro, M., Saltelli, A., 2014. Footprints to nowhere. Ecol. Indic. 46, 610–621. https://doi.org/10.1016/J.ECOLIND.2014.01.030

Gómez-Baggethun, E., Naredo, J.M., 2015. In search of lost time: the rise and fall of limits to growth in international sustainability policy. Sustain. Sci. 10, 385–395. https://doi.org/10.1007/S11625-015-0308-6/METRICS

González de Molina, M., Soto Fernández, D., Guzmán Casado, G.I., Infante Amate, J., Aguilera Fernández, E., Vila Traver, R., García Ruiz, R., 2019. Historia de la agricultura española desde una perspectiva biofísica 1900-2010. Gobierno de España. Ministerio de Agricultura, Pesca y Alimentación, Madrid.

González de Molina, M., Toledo, V.M., 2014. The Social Metabolism. A Socio-Ecological Theory of Historical Change. Springer International Publishing, Berlin.

Goodland, R.J.A., Daly, H.E., El Serafy, S., 1993. The Urgent Need for Rapid Transition to Global Environmental Sustainability. Environ. Conserv. 20, 297–309. https://doi.org/10.1017/S0376892900023481

Graeber, D., 2013. It is value that brings universes into being. HAU J. Ethnogr. Theory. 3, 219–243. https://doi.org/10.14318/HAU3.2.012

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., 2016. Social Ecology. Society-Nature Relations across Time and Space. Springer International Publishing, Switzerland.

Haberl, H., Schmid, M., Haas, W., Wiedenhofer, D., Rau, H., Winiwarter, V., 2021. Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism. Ecol. Econ. 182, 106949. https://doi.org/10.1016/J.ECOLECON.2021.106949

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2

Hall, C.A.S., Klitgaard, K., 2018. Energy and the wealth of nations: An introduction to biophysical economics (2nd Ed). Springer International Publishing, Cham, Switzerland.

Harvey, D., 2010. A Companion to Marx's Capital. Verso, London-New York.

Harvey, D., 2006. The Limits to Capital. Verso, London-New York.

Hausknost, D., 2023. Opacity and Transparency On the 'Passive Legitimacy' of Capitalist Democracy. Theoria 70, 26–53. https://doi.org/10.3167/th.2023.7017702

Hickel, J., Dorninger, C., Wieland, H., Suwandi, I., 2022. Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015. Glob.

Environ. Chang. 73, 102467. https://doi.org/10.1016/J.GLOENVCHA.2022.102467

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. U. S. A. 109, 3232–3237. https://doi.org/10.1073/PNAS.1109936109/SUPPL_FILE/PNAS.1109936109_SI.PDF

Infante Amate, J., González de Molina, M., Toledo, V.M., 2017. El metabolismo social. Historia, métodos y principales aportaciones. Rev. Iberoam. Econ. Ecológica 27, 130–152.

Jasanoff, S., Kim, S.H., 2015. Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power. University of Chicago Press, Chicago.

Jevons, W.S., 1865. The Coal Question. An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal Mines. August M. Kelley, New York.

Kallis, G., Gómez-Baggethun, E., Zografos, C., 2013. To value or not to value? That is not the question. Ecol. Econ. 94, 97–105. https://doi.org/10.1016/J.ECOLECON.2013.07.002

Kapp, W., 1978. The Social Costs of Business Enterprise, [1963] 2nd Ed. Spokesman, Nottingham.

Kapp, W., 1974. Environmental Policies and Development Planning in Contemporary China and Other Essays. Mouton, The Hague.

Kerschner, C., O'Neill, D.W., 2015. Economic growth and sustainability, in: Kopnina, H., Shoreman-Ouimet, E. (Eds.), Sustainability. Routledge, London, pp. 243–276.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use, GDP and population during the 20th century. Ecol. Econ. 68, 2696–2705. https://doi.org/10.1016/J.ECOLECON.2009.05.007

Krugman, P., Wells, R., 2006. Introducción a la Economía: Microeconomía. Reverte, Barcelona.

Leontief, W., 1986. Input-Output Economics, 2nd ed. Oxford University Press, New York.

Liebig von, J., 1840. Principles of Agricultural Chemistry, with Special Reference to the Late Researches Made in England. English Edition (1855). Walton & Maberly, London.

Lotka, A.J., 1925. Elements of Physical Biology. Williams & Wilkins Company, Baltimore.

Lotka, A.J., 1922. Contribution to the energetics of evolution. Proc. Natl. Acad. Sci. 8, 147–151. https://doi.org/10.1073/pnas.8.6.147.

Macy, J., Johnstone, C., 2012. Active Hope: How We Face the Mess We're Without Going Crazy. New World Library, Novato, California.

MAGIC Consortium, T., 2020. The Nexus Times. Megaloceros Press, Bergen.

Martinez-Alier, J., 1987. Ecological Economics. Blackwell, Oxford/New York.

Martinez-Alier, J., Munda, G., O'Neill, J., 1998. Weak comparability of values as a foundation for Ecological Economics. Ecol. Econ. 26, 277–286.

Martinez-Alier, J., Muradian, R., 2015. Taking stock: the keystones of ecological economics, in: Martínez-Alier, J., Muradian, R. (Eds.), Handbook of Ecological Economics. Edward Elgar Publishing, Cheltenham, pp. 1-25.

Martinez-Alier, J., Roca-Jusmet, J., 2013. Economía ecológica y política ambiental. Fondo de Cultura Económica, Ciudad de México.

Matuštík, J., Kočí, V., 2021. What is a footprint? A conceptual analysis of environmental footprint indicators. J. Clean. Prod. 285, 124833. https://doi.org/10.1016/J.JCLEPRO.2020.124833

Mayumi, K., Renner, A., 2023. Reconsidering the Privileged Powers of Banks. Foundations of Sovereign Money, Wealth and Real Capital for Sustainability. Palgrave Macmillan, Singapore.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press, Cambridge.

Moleschott, J., 1857. Der kreislauf des lebens. Von Zabern, Mainz.

Naredo, J.M., 2019. Taxonomía del lucro. Siglo XXI, Madrid.

Naredo, J.M., 2015. La Economía en Evolución : Historia y Perspectivas de las Categorías Básicas del Pensamiento Económico (4aed.). Siglo XXI, Madrid.

Naredo, J.M., 2010. Raíces económicas del deterioro ecológico y social. Siglo XXI, Madrid.

O'Neill, D.W., 2015. Gross domestic product, in: D'Alisa, G., Demaria, F., Kallis, G. (Eds.), Degrowth: A Vocabulary for a New Era. Routledge, New York, pp. 103–108.

O'Neill, J., 2017. Pluralism and incommensurability, in: Spash, C.L. (Ed.), Routledge Handbook of Ecological Economics : Nature and Society. Routledge, New York, pp. 227–236.

O'Neill, J., Uebel, T., 2015. Analytical philosophy and ecological economics : Handbook of Ecological Economics, in: Martínez Alier, J., Muradian, R. (Eds.), Handbook of Ecological Economics. Edward Elgar Publishing, pp. 48-73.

Oreskes, N., 2021. Science on a Mission: How Military Funding Shaped What We Do and Don't Know about the Ocean. University of California Press, Chicago.

Ostwald, W., 1912. Der energetische Imperatiw. Akademische Verlagsgesellschaft, Leipzig.

Ostwald, W., 1909. Energetische Grundlagen der Kulturwissenschaften. Vorvaert, Leipzig.

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Koukkanen, A., Spangenberg, J.H., 2019. Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability. A study edited by the European Environmental Bureau. Brussels.

Pascual, U., Balvanera, P., Anderson, C.B., Chaplin-Kramer, R., Christie, M., González-Jiménez, D., Martin, A., Raymond, C.M., Termansen, M., Vatn, A., Athayde, S., Baptiste, B., Barton, D.N., Jacobs, S., Kelemen, E., Kumar, R., Lazos, E., Mwampamba, T.H., Nakangu, B., O'Farrell, P., Subramanian, S.M., van Noordwijk, M., Ahn, S.E., Amaruzaman, S., Amin, A.M., Arias-Arévalo, P., Arroyo-Robles, G., Cantú-Fernández, M., Castro, A.J., Contreras, V., De Vos, A., Dendoncker, N., Engel, S., Eser, U., Faith, D.P., Filyushkina, A., Ghazi, H., Gómez-Baggethun, E., Gould, R.K., Guibrunet, L., Gundimeda, H., Hahn, T., Harmáčková, Z. V., Hernández-Blanco, M., Horcea-Milcu, A.I., Huambachano, M., Wicher, N.L.H., Aydın, C.İ., Islar, M., Koessler, A.K., Kenter, J.O., Kosmus, M., Lee, H., Leimona, B., Lele, S., Lenzi, D., Lliso, B., Mannetti, L.M., Merçon, J., Monroy-Sais, A.S., Mukherjee, N., Muraca, B., Muradian, R., Murali, R., Nelson, S.H., Nemogá-Soto, G.R., Ngouhouo-Poufoun, J., Niamir, A., Nuesiri, E., Nyumba, T.O., Özkaynak, B., Palomo, I., Pandit, R., Pawłowska-Mainville, A., Porter-Bolland, L., Quaas, M., Rode, J., Rozzi, R., Sachdeva, S., Samakov, A., Schaafsma, M., Sitas, N., Ungar, P., Yiu, E., Yoshida, Y., Zent, E., 2023. Diverse values of nature for sustainability. Nat. 2023 6207975 620, 813–823. https://doi.org/10.1038/s41586-023-06406-9

Pauliuk, S., Majeau-Bettez, G., Müller, D.B., 2015. A general system structure and accounting framework for socioeconomic metabolism. J. Ind. Ecol. 19, 728–741.

Pirgmaier, E., Steinberger, J.K., 2019. Roots, riots and radical change—a road less travelled for ecological economics. Sustainability 11. https://doi.org/10.3390/su11072001

Plumecocq, G., 2014. The second generation of ecological economics: How far has the apple fallen from the tree? Ecol. Econ. 107, 457–468. https://doi.org/10.1016/J.ECOLECON.2014.09.020

Podolinsky, S., 1883. Menschliche arbeit und einheit der kraft. Die Neue Zeit 1, 413–424.

Raz, J., 1986. The Morality of Freedom. Clarendon, Oxford.

Rees, W.E., Wackernagel, M., 1996. Urban ecological footprints: Why cities cannot be sustainable - and why they are a key to sustainability. Environ. Impact Assess. Rev. 16, 223–248.

Røpke, I., 2005. Trends in the development of ecological economics from the late 1980s to the early 2000s. Ecol. Econ. 55, 262–290.

Røpke, I., 2004. The early history of modern ecological economics. Ecol. Econ. 50, 293–314.

Rosas-Sánchez, G.A., 2023. El abandono progresivo de las cuestiones ambientales en el pensamiento económico: hacia la reivindicación de la economía ecológica. Papeles Relac. ecosociales y camnbio Glob. 164, 121–132.

Schumpeter, J.A., 1954. History of Economic Analysis. Oxford University Press, Oxford.

Smil, V., 2015. Power Density: A key to understanding energy sources and uses. MIT Press, Cambridge.

Smil, V., 2008. Energy in Nature and Society: General Energetics of Complex Systems. MIT Press, Cambridge.

Soddy, F., 1926. Wealth, Virtual Wealth and Debt: The Solution of the Economic Paradox. George Allen & Unwin Ltd., London.

Soddy, F., 1912. Matter and energy. Oxford University Press, London.

Spash, C.L., 2020a. A tale of three paradigms: Realising the revolutionary potential of ecological economics. Ecol. Econ. 169, 106518. https://doi.org/10.1016/j.ecolecon.2019.106518

Spash, C.L., 2020b. Fundamentos para una economía ecológica y social. Fuhem Ecosocial y Libros de la Catarata, Madrid.

Spash, C.L., 2017. Social Ecological Economics, in: Spash, C.L. (Ed.), Routledge Handbook of Ecological Economics : Nature and Society. Routledge, New York, pp. 3–16.

Spash, C.L., 2015. The content, direction and philosophy of ecological economics, in: Martinez-Alier, J., Muradian, R. (Eds.), Handbook of Ecological Economics. Edward Elgar, Cheltenham, pp. 26–47.

Spash, C.L., 2012. New foundations for ecological economics. Ecol. Econ. 77, 36–47.

https://doi.org/10.1016/j.ecolecon.2012.02.004.

Spash, C.L., Ryan, A., 2012. Economic Schools of Thought on the Environment: Investigating Unity and Division. Cambridge J. Econ. 36, 1091–1121. https://doi.org/10.1093/CJE/BES023

Spash, C.L., Smith, T., 2019. Of ecosystems and economies:re-connecting economies with reality. Real-World Econ. Rev. 19, 221-229.

Steward, J.H., 1968. The concept and method of Cultural Ecology, in: Sills, D.L. (Ed.), International Encyclopedia of the Social Sciences. Macmillan Co., New York.

Swyngedouw, E., 2006. Metabolic urbanization: the making of cyborg cities, in: Heynen, N., Kaika, M., Swyngedouw, E. (Eds.), In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism. Routledge, New York, pp. 21–40.

Toledo, V.M., 2008. Metabolismos rurales: hacia una teoría económico-ecológica de la apropiación de la naturaleza. Rev. Iberoam. Econ. Ecológica 7, 1–26.

UNEP, 2011. Decoupling Resource Use and Environmental Impacts from Economic Growth. UN Environment Programme, Paris.

van den Bergh, J.C.J.M., Grazi, F., 2014. Ecological Footprint Policy? Land Use as an Environmental Indicator. J. Ind. Ecol. 18, 10–19. https://doi.org/10.1111/JIEC.12045

Vatn, A., 2005. Institutions and the Environment. Edward Elgar Publishing, Northampton, MA.

Vernadsky, V., 1926. The Biosphere (first published in Russian). English version (1986). Synergetic Press, Oracle, AZ.

Victor, P.A., 2015. Growth, in: D'Alisa, G., Demaria, F., Kallis, G. (Eds.), Degrowth: A Vocabulary for a New Era. Routledge, New York, pp. 109–112.

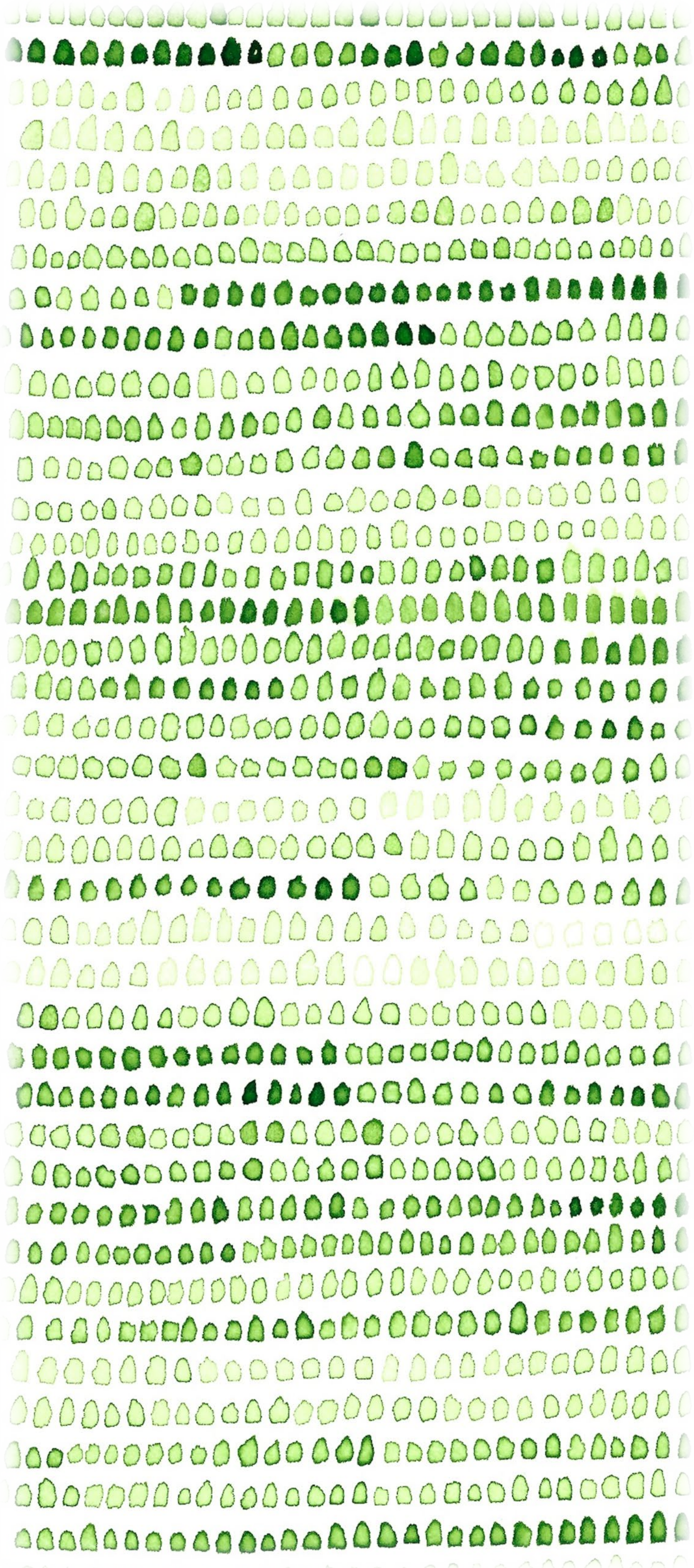
White, L.A., 1943. Energy and the evolution of culture. Am. Anthropol. 45, 335–356.

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 3107. https://doi.org/10.1038/s41467-020-16941-y

Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities — Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. Ecol. Econ. 61, 15–26. https://doi.org/10.1016/J.ECOLECON.2006.12.003

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. U. S. A. 112, 6271–6276. https://doi.org/10.1073/PNAS.1220362110/SUPPL_FILE/SD01.XLSX

Chapter 3



3. Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) revisited: synthesising and updating the theoretical foundations[♦].

> "Sé que vivimos desconectados
> de nuestras acciones.
> Sé que no podemos seguir viviendo
> en un mundo así".
> Antonio Orihuela[*].

3.1. Introduction.

Following the identification of CE's limitations in addressing environmental issues in the previous chapter, it is time to revisit MuSIASEM, searching for solutions that enable us to perform robust sustainability analyses. MuSIASEM (Giampietro and Mayumi, 2000a, 2000b) is an accounting scheme to characterise how societies use natural and human-created goods and how social-economic systems simultaneously depend on and place pressures on processes in ecosystems. The foundations for MuSIASEM were laid out during the 1990s in response to the need to integrate the findings of complex system science (Giampietro, 2019a; Giampietro et al., 2014, 2013, 2012; Giampietro and Renner, 2020; Renner et al., 2020b) into sustainability assessments, the latter requiring dealing with economic and ecological processes simultaneously while considering that different space-time boundaries characterise both processes. This biophysically grounded framework is open to pluralities of values and concerns, a feature that makes the methodology capable of handling incommensurability issues[8] identified as relevant in sustainability science research agendas (Weitz et al., 2018).

Over the more than 20 years since its introduction, MuSIASEM accounting has been used for different integrated assessments. Moreover, various improvements have crystallised into a more sophisticated version[9]. Indeed, MuSIASEM has advanced in handling quantitatively multiple dimensions (energy, water, food, raw materials, emissions, waste, human activity, land use, power capacity) and multiple levels (process, sub-sector, sector, average society) across scales (per hour, per year, per m^2).

[♦] This chapter is mainly based on Larrabeiti-Rodríguez and Velasco-Fernández (2022).

[*] Extract from the poem *Complicidad*, in Orihuela, A. (2023). Sin Fin. Antología personal 1993-2023. Gato Encerrado, Toledo, p. 106.

[8] As we saw in Chapter 2, incommensurability means there is no common evaluation standard for certain values belonging to different dimensions (Martinez-Alier et al., 1998).

[9] So-called MuSIASEM 2.0 was developed within the Horizon 2020 project MAGIC (short for Moving Towards Adaptive Governance in Complexity — https://magic-nexus.eu/).

Epistemological tools such as the end-use and environmental pressure matrices have been refined, considering trade effects. Additionally, ontological issues have also gained in depth. I firmly believe that all these advances must be thoroughly discussed and synthesised, referencing the most recent publications using the methodology, to ensure the continued robustness and relevance of MuSIASEM in sustainability analyses.

In a nutshell, the aim of this chapter is threefold: (i) to rediscuss and update the relevance of the theoretical foundations of MuSIASEM; (ii) to provide a synthetic overview of the analytical tools available in the methodology to assess different aspects of the current sustainability crisis; and (iii) to clarify the not always well-understood peculiarities, potentialities and limitations of the analytical framework. This should lead to an informed application of MuSIASEM and a greater understanding of complementarities with other methodologies. In this way, MuSIASEM could bridge and complement analysis focused on processes and objects, such as Life Cycle Analysis (LCA) (European Union Joint Research Center, 2010), with a systemic perspective and analysis focused on flows such as MEFA (Fischer-Kowalski and Haberl, 2007) with the critical entanglement with fund elements[10].

The chapter is organised as follows: section 3.2 presents the basic ideas behind MuSIASEM regarding the characterisation of social-economic systems, the economic process, and the sustainability predicament. Section 3.3 discusses relevant theoretical concepts needed to develop applications based on the richness of its theoretical foundations. Each concept emphasises a pertinent feature or level of observation to be considered. Section 3.4 closes with some limitations and concluding remarks.

3.2. MuSIASEM: revisiting and updating its heterodox rationale.

Building on Spash (2015), a vision seems to be required before we can proceed. From this agreement, empirical reflection can follow. Therefore, the basis of MuSIASEM's understanding of social-economic systems, the economic process and sustainability are synthesised.

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[10] Drawing on Georgescu-Roegen (1971), fund elements maintain their identity during analytical representation. Fund elements include human activity, land, and sustainably managed aquifers. On the other hand, flow elements change their identity during analytical representation. Examples of typical flow elements include energy, food, and waste.

3.2.1. How does MuSIASEM view social-economic systems?

From the MuSIASEM perspective, social and natural systems are complex adaptive systems (Gell-Mann, 1994; Holland, 2006, 1995) and should be studied considering them entangled (Giampietro, 2019b). Treating a system as complex presents several epistemological challenges (Ahl and Allen, 1996). The behaviour of the whole is not evident from the study of its parts (Cilliers, 1998). Patterns must be considered and understood as a specific configuration of relationships (Capra, 1996). Concerning this challenge, MuSIASEM applies a systemic thinking framework (Giampietro et al., 2006) where social-economic systems are considered integrated wholes whose properties are determined by the dynamic connections among functional and structural elements (e.g. transport function could be performed by different structural elements such as a bike or a scooter; a bike could perform various functions of transport or recreation). The methodology enables a narrative where the performance of the whole social-economic system is tied to the “emergent property” determined by the interaction of its constituent components, i.e. hierarchically organised, lower-level functional components (e.g. economic sectors and subsectors) made up of structural elements. These constituent components express different functions associated with various valuable outputs or end uses (i.e., what society requires). In turn, they are constrained by biophysical limits, such as resource availability or performance capacity, associated with the characteristics of the structural elements shaping them (i.e. what is admissible in biophysical terms). For example, the agriculture sector generates several useful outputs, such as biomass input to the energy sector or food inputs to the household sector. The supply of all these inputs is constrained by the amount and characteristics of the structural elements that make up the agriculture sector, i.e. the productive capacity of different types of farms determined by technical viability (e.g. labour and capital), and also by the availability of ecological services, i.e. the availability of production factors such as soil, solar radiation or biodiversity, made available by natural processes. At the same time, production processes in the agricultural sector require inputs from the other compartments of society. That is, the other compartments of society must be willing and capable of providing the necessary secondary inputs needed by the agricultural sector to operate (e.g. labour, technology, energy carriers) in exchange for the products of this sector.

MuSIASEM links the perception and representation of an economic system with concepts such as interdependence and complementarity. In this framework, a social-economic system is considered a relational metabolic network in which constituent components stabilise each other in an impredicative set of relations (Renner et al., 2020b). In other words, we should expect that social-economic systems have a self-referential pattern of organisation determining a network of relationships in which the function of each component has to be integrated and coordinated with the others to sustain and reproduce the whole network. Thus, the constituent components of an archetypical modern social-economic system depend on each other in terms of essential inputs (see Figure 3.1): (i) the household sector uses inputs produced by all the other constituent components to reproduce itself (i.e. nurturing and care work) and to supply hours of human activity (labour and consumption) to the rest of the constituent components; (ii) primary sectors (agriculture, energy and mining) use human activity that comes from the household, primary inputs from the environment (i.e. biosphere inputs), and secondary inputs from the other constituent components to supply secondary inputs of food, energy and raw materials to the others; (iii) the manufacturing sector and construction sector uses human activity and secondary inputs to supply technology and infrastructures (i.e. power capacity) to the entire society; and (iv) the service and government sector uses human activity and secondary inputs to reproduce institutions and maintain the quality of life of the people that ask for services (Velasco-Fernández et al., 2020a). Moreover, this set of relations between constituent components (in the technosphere) requires, in turn, constant interaction with the environment, dumping waste and emissions (biosphere outputs) and obtaining goods and services (biosphere inputs). The consideration of this necessary relationship implies modifying our level of observation. What we see is not an isolated, self-sufficient economic system (with exchanges only considered in monetary terms) but a social-ecological system (SES) (Berkes et al., 2003; Holling, 2001) determined by the activities expressed by a given set of ecosystems —in the biosphere— and a given set of social actors and institutions —in the technosphere.

3.2.2. How does MuSIASEM view the economic process?

Inspired by the work of Georgescu-Roegen (1971), MuSIASEM also invites us to rethink the final cause of the economic process. The great biophysical economist considered the enjoyment of life as the ultimate purpose of the economic process. Thus, “value” derives from the perceptions, emotions, and feelings of the psychic structure of society (Luhmann, 1995) and is associated with the affective interactions experienced during the production and consumption of goods and services. Following the same line of reasoning, the ultimate goal of the economic process in MuSIASEM is not to produce as many goods and services as possible —ecosystems and households also produce goods and services— but to ensure the maintenance, reproduction and adaptability of their constituent components. Indeed, the production and consumption of goods and services is only relevant if this process is capable of expressing the emergent property typical of complex adaptive systems, i.e. reproducing themselves while learning how to adapt to the changing conditions of their contexts (Giampietro and Mayumi, 2018). This change in perspective moves attention from productivism to a different set of essential factors defining the economic process. This shift is in line with a vision of economics as a science of social provisioning which seeks to understand how societies organise the flow of goods and services necessary to maintain and reproduce themselves in the context of historically specific systems and structures (Pirgmaier and Steinberger, 2019; Spash, 2020).

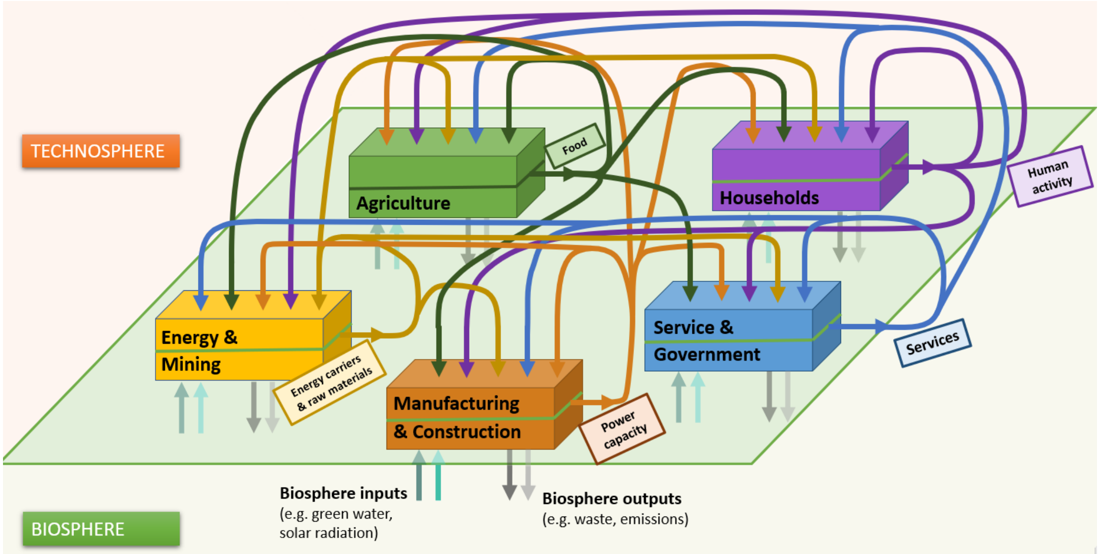

Figure 3.1. Societal constituent components´ entanglements in the technosphere and biosphere. Source: Adapted from Renner et al. (2020b).

With the above in mind, we can conclude that the metabolism of a social-economic system is not an analogy to the biological notion of metabolism for understanding human-nature interactions (Fischer-Kowalski, 1998; Infante Amate et al., 2017) but a fact (Giampietro et al., 2020). Human systems are maintained and renewed through their continuous interactions with the environment. They are integrated wholes inseparably linked to metabolic and dynamic processes of change. Therefore, social-economic systems are metabolic-repair systems of the type explored in relational biology (Renner et al., 2020b) or autopoietic systems (Maturana and Varela, 1980). They can maintain and adapt their identity, i.e., structural elements, functional elements, and emergent property, providing a desirable standard of living for the people living in society through the process of replication, metabolism, and repair.

3.2.3. How does MuSIASEM consider the sustainability of social-economic systems?

MuSIASEM opens the way for a quantitative and qualitative contextualisation of the sustainability of social-economic systems based on studying their metabolic pattern. The metabolic pattern refers to the interdependent conversion processes of energy and materials inputs in a given society used to reproduce itself. This analytical concept makes it possible to study the entanglement of different types of metabolic flows and funds across levels and scales of analysis. If sustainability is understood as the commitment of human societies to preserve the essential elements of their identities in line with environmental constraints (i.e. respecting the biophysical processes and thresholds of the planet and local ecosystems), analysis of the metabolic pattern generates different indicators referring to different levels of observation capable of addressing different sustainability concerns. In this way, it becomes possible to integrate:

1. An external view related to the concept of feasibility and associated with processes outside human control. Feasibility checks the compatibility of the *environmental pressures* related to the metabolic pattern of any society (see section 3.1) with the existence and severity of external biophysical constraints. This involves constraints that result from the interaction of social-economic systems with ecological systems, both on the supply side (e.g. appropriation of primary flows —they cannot be produced by human technology, the first principle of thermodynamics— such as oil, water or minerals, which need primary supply provided by nature) and the sink side (e.g. primary wastes and emissions such as greenhouse gases and plastic waste). This view is translated into a quantitative assessment associated with *the environmental pressure matrix* (EPM). Feasibility is related to the natural constraints limiting production and consumption and raises questions such as: how much land and water are required for producing domestic food consumption? Or are there sufficient lithium reserves to replace the entire fleet of combustion vehicles with electric ones? This analysis could be associated with planetary boundaries (Rockström et al., 2009).

2. An internal view related to the concept of viability and associated with processes under human control. Viability checks the severity of internal biophysical and economic constraints operating inside the social-economic system. These constraints include technological capability, economic viability, and labour supply/shortage. The requirements of these elements are also associated with socio-demographic variables (Velasco-Fernández et al., 2020b) and the terms of

trade (Pérez-Sánchez et al., 2021). One of the critical elements of the methodology is the analysis of the profile of time use as an emergent property of the societal organisation and as a relevant internal constraint in case of a shortage of human time in one or more critical functions in society (Manfroni et al., 2021b). Viability requires characterising the *state*, i.e. looking inside the black box for the internal metabolic characteristics of the structural and functional compartments of the social-economic system. This view is translated into a quantitative assessment associated with *the end-use matrix* (EUM), based on analysis of the use of secondary inputs —produced by human exploitation of primary flows and compatible with the different typologies of power capacity that use them to generate end uses— i.e. energy carriers (e.g. electricity, fuels), distributed water for different societal uses, and processed materials. Viability is related to the technical and economic constraints affecting production and consumption. It raises questions such as: how are the secondary inputs used in different societal compartments to reproduce and adapt? What percentage of human activity is allocated to the primary sector? Or, what is the welfare level (measured as the percentage of human activity assigned to the service sector) of the society?

3. A normative view related to the concept of desirability. Desirability refers to the perceived acceptability of the living conditions and moral responsibility associated with the expression of the metabolic pattern. This expression makes it possible to produce a set of social practices (Shove et al., 2012) where affective and technical relations are entangled in either sustainable or unsustainable ways. This implies that it is necessary to extend the analysis beyond biophysical variables by considering values, desires, beliefs, and cultural, social, and political arrangements to assess desirability. Addressing the desirability of the metabolic pattern of a social-economic system requires a reflection that calls for a post-normal science rationale (Funtowicz and Ravetz, 1993), i.e. forms of knowledge based on participatory and deliberative processes. It raises questions such as: assuming that a transition to 100% renewable energy is feasible (i.e. possible materially, finding enough minerals and land to build the energy infrastructure) and viable (i.e. possible socioeconomically), will the readjustment in everyday practices because of this transition find social acceptance?

MuSIASEM establishes a framework of analysis capable of establishing a set of expected relations concerning these different aspects of sustainability (feasibility, viability, and desirability). An integrated analysis of these various aspects requires the simultaneous use of non-equivalent and non-reducible definitions of constraints or limits of a different nature (external limits associated with feasibility and internal limits related to viability and desirability). To this end, MuSIASEM uses a toolkit comprising an interrelated set of matrices that supplies an integrated, multi-scale, quantitative representation of the functioning of the metabolic pattern. It also explicitly considers the degree of openness of the social-economic system determined by trade, i.e. accounting not only for the biophysical processes taking place within each system's geographical boundary (e.g. fuels refined in Spain) but also for those supporting each system's metabolic pattern, taking place elsewhere (e.g. oil extracted elsewhere to produce the fuels refined in Spain). This tool-kit can be used: (i) in diagnostic mode to obtain an in-depth understanding of the biophysical foundations of the system under analysis, identifying critical aspects in the form of indicators that can be tailored to relevant sustainability concerns; and (ii) in anticipatory mode, exploring scenarios based on the adoption of benchmarks, raising "what if" questions concerning possible reactions to changes introduced (policies and innovations). Because of the consideration of the effects of externalisation (the degree of openness), the toolkit characterising the factors determining the state and the pressures is organised into four matrices (Figure 3.2). Two different types of matrices are used to describe the factors of viability, observed inside the border —the internal EUM— and outside the border —the external EUM. And two matrices are used to characterise the factors of feasibility, observed inside the border —the internal EPM— and outside the border —the external EPM.

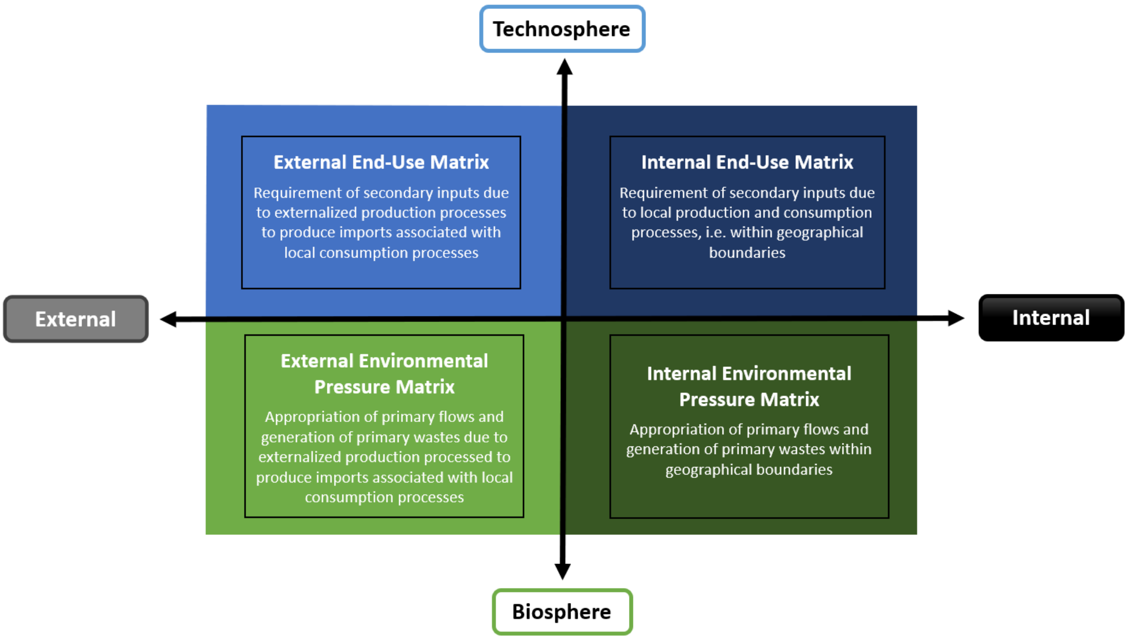

Figure 3.2. The MuSIASEM toolkit is comprised of an interrelated set of matrices. Source: Own elaboration.

Practical examples in which this analytical toolkit is used in diagnostic mode can be found, among others, in the characterisation of the uses of different forms of energy carriers (electricity, heat, fuels) for the various tasks performed in the city of Barcelona, showing how commuters and tourists affect energy consumption per capita targets (Pérez-Sánchez et al., 2019); the analysis of the environmental and economic performance of different economic activities in the Mediterranean island of Menorca, exposing the tensions between economic productivity and environmental pressures (Marcos-Valls et al., 2020); or, pointing out the impossibility for the EU of re-internalizing the production of its massive feed imports (Cadillo-Benalcazar et al., 2020b). On the other hand, a practical example of using this analytical toolkit in anticipation mode can be found in Renner et al. (2020a), which uncovers blue water and land requirements breaching environmental limits if a dramatic re-internalization of agricultural production takes place in the EU.

3.3. MuSIASEM key theoretical concepts.

This section discusses and updates critical theoretical concepts in the literature on MuSIASEM, which are not always well explained and understood. Each concept springs from different roots within the tree of complexity science and touches on key aspects to consider. Table 3.1 summarises their main characteristics.

3.3.1. State-pressure relations.

◊ Main idea.

Human societies' primary problem is sustaining themselves. Social sustainability, i.e., maintaining a particular state in the technosphere (associated with positive or valued parts of the current way of life), is irremediably linked to environmental pressures and impacts on the biosphere.

◊ Theoretical background.

Different narratives developed in the field of complexity suggest a strong analogy between the processes of self-organisation of ecological and social systems (Giampietro, 2019a; Giampietro and Renner, 2020; Odum, 1971; Simon, 1962). Both classes are composed of open systems requiring favourable boundary conditions. According to classical thermodynamics, their states are associated with a large generation of positive entropy and, therefore, considered improbable. The existence of complex metabolic systems, such as a modern social-economic system, can only be explained under a perspective of non-equilibrium thermodynamics using the concept of dissipative structure (Nicolis and Prigogine, 1977; Prigogine and Glansdorff, 1971). Social-economic systems are dissipative in that they have structures that cannot be associated with the stability of solids: they tend to degrade and disappear into the environment when the flow of inputs is interrupted (they can literally die). Consequently, these systems must be capable of monitoring and reacting to changes in their surroundings to remain capable of using flows of negative entropy.

Table 3.1. Common theoretical concepts in the literature on MuSIASEM.

Theoretical concept	***Field***	***Level of observation***	***Main characteristic***
State-pressure relations	Non-equilibrium Thermodynamics (Nicolis and Prigogine, 1977; Prigogine and Glansdorff, 1971)	Dissipative structures	Social-economic systems are open systems whose structures and functions (the STATE) are stabilised by a continuous flow of inputs taken from the environment (energy and matter) and a continuous flow of outputs released to the environment (wastes and emissions), which leads to an acceptable PRESSURE on the environment.
Holon and holarchies	Hierarchy Theory (Ahl and Allen, 1996; Allen and Starr, 1982; Giampietro, 1994; Giampietro et al., 2006)	Semantic relations between structural and functional types across levels	Co-existence of relevant aspects of the system that are tangible (biophysical) and intangible (notional) when perceiving and representing a complex system.
Relational Analysis	Relational Biology (Louie, 2017; Rashevsky, 1935; Rosen, 2005, 2000)	Metabolic processors as a tool to describe both structural and functional elements	A processor describes a pattern of expected relations (that can be defined at different levels) between profiles of inputs and profiles of outputs associated with the expression of a specific function using two categories of accounting: (i) concerning the interaction with other parts inside the technosphere (secondary inputs and outputs); and (ii) about the interaction with the biosphere (primary flows on the supply and sink side).
Semiotic process	Biosemiotics (Barbieri, 2019; Emmeche and Kull, 2011; Kull et al., 2009; Pattee, 1995)	Human societies not only exchange materials and energy with the environment but also information	The existence of entities which organise our experience, even though they are not tangible (emotions, fears, beliefs, political processes). These answer questions such as “Who are we as a society? Or “What are our goals?” determining the metabolic relation with nature, i.e. the expression of the metabolic pattern.
Dynamic Energy Budget	Theoretical Ecology (Ulanowicz, 1986)	Net energy supply and the complex organisation of metabolic networks	Any metabolic system, including social-economic systems, must invest energy in (i) getting energy and other material inputs (in the hypercycle part)—catabolism; and (ii) expressing other required behaviours (in the dissipative part), such as maintaining and updating social institutions—anabolism.

In this regard, Schrödinger (1967) proposed the term “negentropy” as the reciprocal of entropy. Living systems can reduce their internal entropy (or increase their negentropy or internal order) at the expense of the free energy taken from the environment and returned to it in a degraded form. In particular, the flows of negative entropy available in the environment (favourable boundary conditions associated with needed primary resources, e.g. fertile soil) are used to sustain a process of exergy degradation, i.e. a process of conversion of secondary inputs (e.g. food) into useful work carried out under expected and controlled conditions. That is, the environmental pressures sustained by the environment —(-dSe) using the iconic representation proposed by Prigogine (1961) —compensates for the positive entropy generation rates (+dSi) associated with the maintenance of the state of the complex internal organisation.

◊ Why is the state-pressure concept important in MuSIASEM?
MuSIASEM uses Georgescu-Roegen's flow-fund model, his most highly-developed analytical contribution after the 1970s (Couix, 2020), under a framework of non-equilibrium thermodynamics to improve the accounting for state-pressure relations. Funds are the underpinning components of SES, belonging to the biosphere (e.g. soils, aquifers) or the technosphere (e.g. human activity, power capacity). Flows may be natural resources (e.g. primary flows such as crude oil or solar energy) or transformed resources (e.g. secondary inputs) such as blue water[11] or energy carriers and also include wastes, i.e. unwanted by-products such as CO_2 emissions. The distinction between funds and flows is essential to define a metabolic system and characterise its metabolic pattern, both (i) in quantitative terms (the size of the flows and the funds) and (ii) in qualitative terms when considering flow/fund ratios and fund allocation patterns (Velasco-Fernández et al., 2020b). By looking at the size of fund elements and their metabolic rate (flow rate per unit of fund) in the technosphere compared to the size of ecological funds and their metabolic rate in the embedding environment, we can study the factors determining a given state-pressure relation. This coupling of the size of the fund elements of the society with the size of funds elements of the ecosystems helps to identify unsustainable use of biophysical resources.

More profoundly, the distinction between funds and flows allows consideration of:

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[11] The definition of blue water includes the fraction of water found in lakes, rivers, and reservoirs that usually needs to be distributed. On the other hand, green water is defined as the water contained in the soil that can be used only by plants for evapotranspiration, and that can neither be distributed nor treated before use (Giampietro et al., 2014).

1. The key features in the dissipative structures of the system in the technosphere, i.e. the elements that have to be preserved and reproduced by the metabolic process to maintain the system's identity associated with the state's expression.
2. Identifying the characteristics of the specific flows that these dissipative structures require, i.e. the materials and energy transformed during the metabolic process. This issue is a crucial feature needed to guarantee the quality of the material and flow accounting. Electricity is an energy input for a refrigerator but not for an aeroplane. In contrast, ham is food for a Protestant but not for an Islamic and undrinkable water could be suitable for irrigation but not for human consumption. Therefore, the level of resource consumption (i.e. the flows) per unit of fund size, i.e. the metabolic rates, can only be described after having identified the category of accounting used to measure the type of flows. Consequently, not all Joules of "energy" and not all kilograms of "matter" are the same when analysing the metabolic pattern of a specific system.
3. The definition of the sociometabolic functions maintained over the analytical time and space boundaries associated with valuable tasks for society. A given element, e.g. a farm characterised in terms of human activity and land use, can use a mix of secondary inputs taken from society, e.g. blue water, energy carriers and feed types, because it produces a given number of critical flows, e.g. food products. This task is considered helpful concerning the system the farm belongs to, i.e., feeding people in a national economy.
4. Identifying pressures and environmental impacts when tracking the connection between the consumption of secondary inputs in the technosphere and the requirement of primary supply and sink in the biosphere. Thus, the flows consumed by society are either coming from fund-flow exploitation (i.e. a sustainable use respecting the rate of generation of resources and assimilative capacity of ecological funds) or stock-flow exploitation (i.e. an unsustainable use of accumulated resources that is depleting stocks, filling sinks, or damaging ecological funds). Analysing these relations provides valuable information about the type and seriousness of environmental pressures.
5. A distinction between sustainability issues dealing with analysing external (feasibility) and internal (viability) processes. This differentiation stresses the fact that the metabolic pace of a system depends on both the accessibility of adequate input flows from the environment (i.e. primary flows) and the capacity of internal

factors which have to do with funds' capacity under human control of processing available flows during the conversion (producing secondary inputs and outputs).

To be clear, studying state-pressure relations using a flow-fund model enables an approach that contrasts with that offered by MEFA, the other primary method for analysing the economy's metabolism (Gerber and Scheidel, 2018). The latter, influenced by CE's idea of double-entry accounting systems (González de Molina et al., 2019), does not differentiate between different qualities and purposes of flows and provides a representation of the economic system as a "black box" focusing on what gets into and out without considering the differentiation of the various functional parts in terms of secondary flows and funds. The state-pressure concept used in MuSIASEM also provides a more systemic perspective than LCA, usually focused on a comprehensive accounting of all biophysical costs associated with a particular production process. However, both methodologies can be complementary, as Martin et al. (2023) exemplified. Finally, this concept facilitates a clear definition of sustainability: a system is sustainable if its reproduction maintains the integrity of fund elements both in the technosphere and the biosphere.

In practical terms, operationalising the state-pressure concept through the flow-fund model implies that flows are always analysed in relation to funds, never isolated or with other flows. Thus, this accounting not only focuses on quantifying flows but also connects funds (the agents and transformers of processes) and flows (the elements that are utilised and dissipated). In turn, the definition of constituent components and fund and flow elements of the studied system allows for articulating MuSIASEM's toolkit, as shown in Table 3.2. For examples, see Giampietro and Bukkens (2022), where the irrelevance of energy efficiency indicators obtained by calculating flow/flow ratios for sustainability analysis (e.g. carbon intensity or energy intensity indicators) is discussed. Also, Velasco-Fernández et al. (2020b), where a multi-scale flow-fund characterisation is used to show the state-pressure evolution of China due to its modernisation considering human activity as a fund element and energy throughput and value-added as flow elements.

Table 3.2. Definition of constituent components and fund and flow elements for the articulation of the MuSIASEM's toolkit.

Stages for the construction of the MuSIASEM's toolkit
1. DEFINITION
1.1. Identification of the constituent components, i.e. hierarchically organised functional compartments (made of structural elements), associated with the system's metabolism.
1.2. Defining fund elements to characterise constituent components (extensive).
1.3. Defining flow elements used by the selected fund elements (extensive).
1.4. Definition of the metabolic characteristics (flow/fund ratios — intensive).
1.5. Data gathering (top-down/bottom-up approach) across different domains.
2. DIAGNOSIS
Internal and external end-use matrix (EUM).
Internal and external environmental pressure matrix (EPM).
3. ANTICIPATION
Explore the feasibility, viability, and desirability of alternative state-pressure relations to test the sustainability of different scenarios using the available information.

3.3.2. Holon and holarchies.

◊ Main idea.

The pre-analytical definition of "what is observed and how" is essential in determining a quantitative output. The concept of holon points to the elusive nature of complex systems and the impossibility of their unique characterisation.

◊ Theoretical background.

The term "holon" was proposed by Arthur Koestler (1967) to address the epistemological predicament that some entities are, in many senses, wholes but cannot be understood without recognising the contexts in which they interact. Clear candidates for the holon label include cells, organs, individual humans, household communities and entire social-economic systems. Hierarchy theory (Ahl and Allen, 1996; Allen and Giampietro, 2014; Allen and Starr, 1982; Giampietro, 1994) further elaborated on the concept of holarchies (hierarchy of holons), emphasising a presumed hierarchical organisation of complex adaptive systems.

The dual nature of a holon explains the systemic ambivalence found in the perception and representation of the elements of complex systems (Giampietro and Mayumi, 2018). Depending on the scale adopted, "an element" can be considered a structural whole —e.g. a human being made up of organs (the local-scale view)— or a functional part of a higher hierarchical level —e.g. a human being part of a household (the large-scale view). The large-scale view defines a relevant functional type associated with the ability to express an expected behaviour described in relation to the context, i.e. the rest of the network the element belongs to. The local-scale, for cons, defines a pertinent structural type, i.e. the organised structure required to perform the specified function. The concept of holon acknowledges the impossibility of having a substantive one-to-one mapping between types of organised structures and types of functional relations (Giampietro et al., 2006). A functional type can map onto different structural types, and a structural type can have different functions. Besides, both structural and functional types are notional entities that cannot express agency. Agency can only be achieved by an instance of these types, a specific tangible realisation of the combination of the two types. In this sense, when representing elements of complex systems, we think of ideal types (e.g. the farm, the factory, the car). However, we can only observe particular instances of these known typologies (e.g. a specific farm, factory or car) that coincide only in part with the definition of the types.

◊ Why is the concept of holon important in MuSIASEM?
The concept of holon allows an understanding of social-economic systems as holarchies, metabolic networks embedding structure and function. As a result, the transformative services of system components (the transformation of input flows into output flows) can be analysed according to different logics: the input profiles of a series of functional elements and those related to a set of structural elements. The quantitative assessments concerning the two logics do not necessarily map onto each other. The evaluation of the metabolic characteristics of the functional elements —the notional representation of, for instance, “cereal production”— is different from that of the structural elements —the technical representation of varying production processes (e.g. a wheat production system, a rice production system or a corn production system)— all mapping onto the same function, “cereal production” at a higher level. This entails that, depending on the pre-analytical choice of the analysis, i.e. the definition of the structural elements making up the functional component, different quantitative results can be generated to characterise the metabolic characteristics (i.e. inputs and outputs) of a given task. For example, “cereal production” can be defined by using different combinations of production processes (wheat, rice, corn) with different percentages in the mix.

To deal with this issue, MuSIASEM adopts two complementary views when analysing metabolic requirements (Giampietro et al., 2014):

- A top-down view —generating information about functional elements (a notional representation): This logic uses large-scale assessment based on aggregate statistical data to obtain the value of the total amount of inputs used by a given function in the system (e.g., electricity consumption in the residential sector or fuel consumption in the transport sector for mobility).
- A bottom-up view —generating information based on technical characteristics of structural elements: this logic uses local-scale assessments based on direct measurement of coefficients (when dealing with instances of structural elements —e.g. a particular nuclear power plant) or values derived from benchmarks (when dealing with structural types —e.g. a hypothetical nuclear power plant) to characterise local operations of technical elements, i.e. a given technology expressing a biophysical set of transformations (e.g. specific energy requirements for different houses —single or multi-family houses— or for different devices used for mobility in the transport sector —cars, motorcycles and trucks).

In short, considering systems as holarchies implies the need to analyse them from different hierarchical levels and understand their elements as holons. In turn, using two complementary perspectives to define the elements that make up metabolic systems ensures great robustness of the analysis, allowing a double check on the coherence of data referring to different observations. Finally, the difficulty in having a substantive one-to-one mapping between the accounting of the characteristics of structural and functional elements and between the characteristics of types vs instances suggests prudence concerning any quantitative results. For a practical example of the elusive nature of complex systems and the different kinds of uncertainty that may arise when describing a societal energy system, see Di Felice et al. (2019).

3.3.3. Relational analysis.

◊ Main idea.

The metabolic processor concept represents a solution to the epistemological predicament of describing holons, i.e. the characteristics of both structural and functional elements.

◊ Theoretical background.

The term “relational analysis” is based on the term “relational biology” (Louie, 2017; Rashevsky, 1935; Rosen, 2005, 2000) and refers to the existence of expected patterns expressed within metabolic networks. According to the unavoidable existence of state-pressure relations, any metabolic element of an SES, whether a functional compartment or a structural element, is an open system in itself that expresses an expected pattern of "behaviour" in terms of consumption of inputs (coming either from the technosphere or the biosphere) and the expression of a useful function, i.e. the supply of the output. A relational analysis based on the concept of metabolic processors is used to describe the characteristics of the structural and functional elements of SES. More specifically, a metabolic processor conveys five sets of inputs/outputs (see Figure 3.3): (i) secondary inputs from the technosphere (e.g. electricity, fuels, food); (ii) required funds under human control from the technosphere (e.g. hour of human labour, hectares of land use, rate of power capacity); (iii) internal outputs, i.e. useful flows or funds generated by metabolic elements and used by other elements in the technosphere (e.g. the production of food in the agricultural sector or the performance of care activities in the household sector); (iv) primary flows extracted from the biosphere (e.g. green water, water removed from aquifers, coal); and (v) primary wastes discharged into the biosphere (e.g. pollutants, nitrogen from fertilisers, GHG emissions).

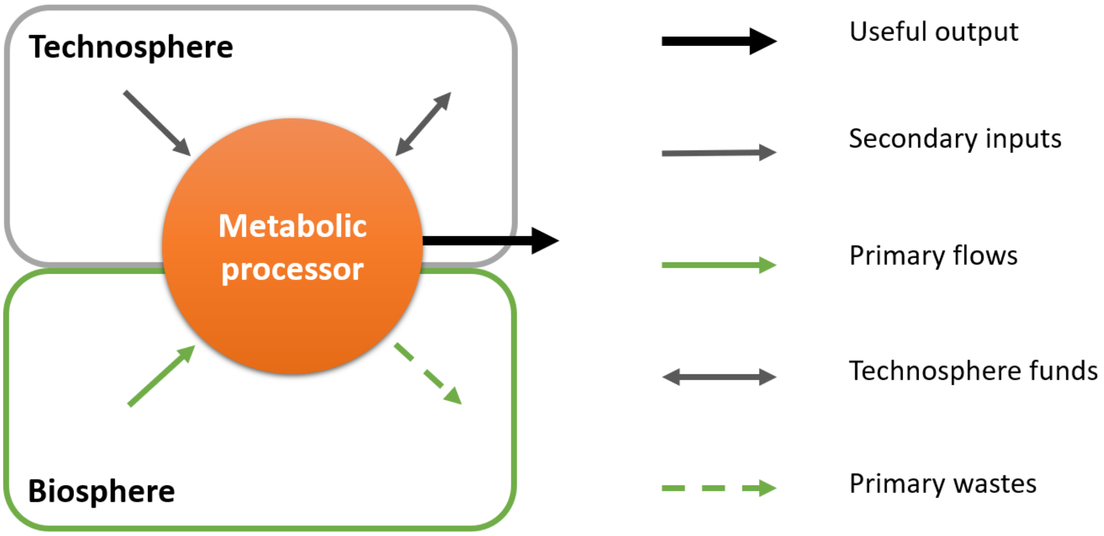

Figure 3.3. The metabolic processor. Source: Adapted from Di Felice et al. (2019).

◊ Why is relational analysis important in MuSIASEM?

Relational analysis enables operationalising a holistic and complex perspective of sustainability issues. This vision is crucial due to several wicked problems (Rittel and Webber, 1973), chicken-egg relations (Giampietro and Mayumi, 2018) and complex scaling effects (Cabello et al., 2019) taking place in SES that are overlooked by reductionist perspectives and silo governance (Scott and Gong, 2021). In this sense, MuSIASEM is capable of capturing in a non-deterministic manner: (i) how the different parts of a system are related, e.g. the production of peak electricity in the energy sector allows the maintenance of a set of social practices in the household sector; (ii) how parts of the system change, e.g. technological innovation of a particular industry; (iii) how the size of the constituent components change, e.g. the relative size of the manufacturing and construction sector in relation to the whole SES; and (iv) how these changes co-evolve by affecting other parts generating systemic change, e.g. the Jevons paradox (Giampietro and Mayumi, 2008). Considering these different types of relations is crucial to understanding why MuSIASEM analysis is so conservative in developing projections over the evolution of SES, building exploratory scenarios rather than predictive ones.

When implementing relational analysis, different nodes of a metabolic network, i.e. the different holons of an SES, can be represented by a set of expected relations over metabolic processors[12]. The input/output flows tied to a metabolic processor are expressed at the level of individual structural elements. Still, they can also be assessed in notional terms at the level of functional elements by associating specific combinations of structural elements (at a given level) to the identity of functional elements (defined at the level above; see Figure 3.4). For instance, we can aggregate the various different processes used in the production of biodiesel (the different crop production processes associated with the operation of organised structures, i.e. the different typologies of biofuel production plants) to obtain the functional element "biodiesel production". Moreover, we can also see the relative contribution of each functional node to the whole (e.g. biodiesel production in relation to the energy system). The aggregate sets of inputs and outputs can then be used to generate matrices (the end-use matrix and the environmental pressure matrix comprising fund and flow elements), characterising the overall SES. However, this way, we get socio-environmental pressures for discussing feasibility and viability aspects. Except for flows directly mapping into global ecosystems as greenhouse gas emissions, analysing potential environmental impacts requires focusing on the individual structural elements (i.e. local production processes affecting ecological funds).

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[12] It is worth mentioning that two databases of structural processors have been generated (Cadillo-Benalcazar and Renner, 2020; Di Felice, 2020) to assess the performance of the food and energy sectors.

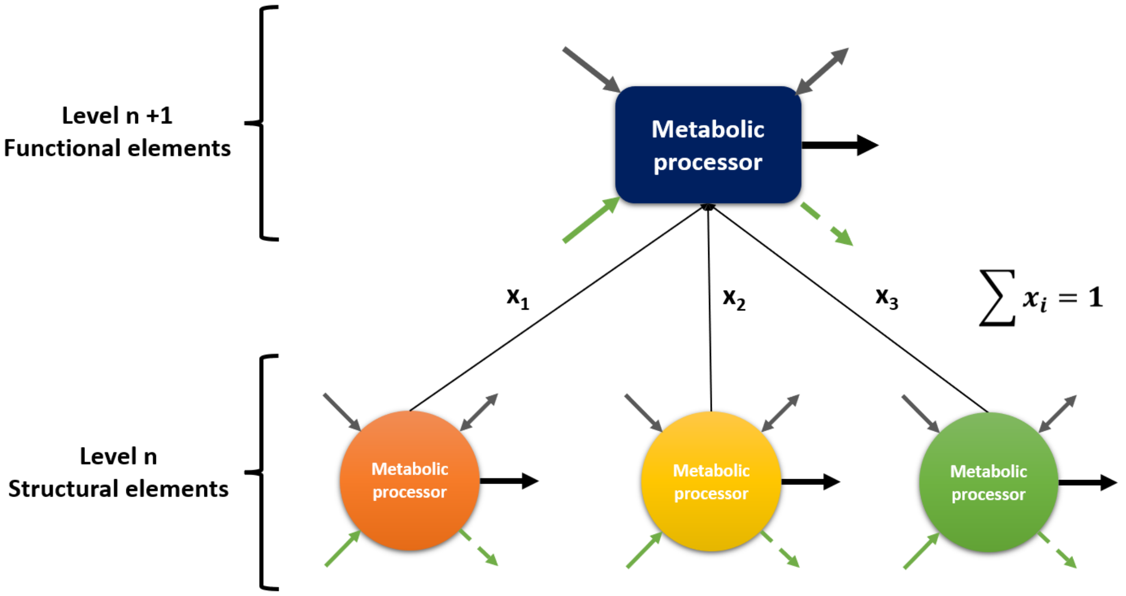

Figure 3.4. Aggregation of structural elements in a higher-level functional element. Source: Adapted from Giampietro et al. (2020).

Different applications have been developed using the concept of the processor to analyse some critical sustainability issues, such as the socio-environmental impacts of the qualitative change of available oil reserves (Manfroni et al., 2021a), the implication of changing an export-oriented energy policy to one that prioritises local consumption (González-López and Giampietro, 2018) or the potential problems with large-scale use of alternative feeds in salmon aquaculture (Cadillo-Benalcazar et al., 2020a).

3.3.4. The semiotic process.

◊ Main idea.

The production of scientific knowledge is vital when generating anticipation. However, the process of scientific advice is embedded in a broader process that defines the identity and priorities to be solved by society as a whole.

◊ Theoretical background.

Whereas simple physical systems may be well understood as simply behaving in a thermodynamic fashion, we cannot understand ecological or social systems without invoking meaning and significance (Barbieri, 2019; Emmeche and Kull, 2011; Giampietro et al., 2006; Giampietro and Renner, 2020; Kull et al., 2009). All living systems are cognitive systems that validate the usefulness of their models through a process of interaction with the external world based on self-regulation from feedback (Capra, 1996). Relevant perceptions of the external world (semantics) are translated into a given representation (syntactics) used to guide action (pragmatics). Results are evaluated against the expected outcome predicted by the model. The knowledge is validated if the living system successfully achieves its goals. If not, new explanatory models must be generated until “semantic closure” is obtained (Pattee, 1995), i.e. when all the steps between semantics, syntactics and pragmatics are coherent concerning the purpose of the final party responsible for evaluating the process.

In the case of human societies, achieving semantic closure is an intricate and conflictive process, especially in sustainability issues where different agents, using non-equivalent criteria, have contrasting goals, perceptions and representations of what should be considered relevant. In this sense, the existence of a political process defining the identity (i.e. what we must sustain) and determining the priorities over the problems to be solved by society as a whole is a particular component of the semiotic process of human societies (Giampietro, 2019a). The semiotic process reveals that value systems are essential to human activity. Different value systems co-exist, and they are never equally influential within society. Due to the existence of power asymmetry in the political process, it is essential to avoid the hegemony of partial and particular perspectives and agendas in the political process in relation to the problems to be solved. A definition of concerns to be addressed that is too narrow, focused on a limited set of narratives and reflecting only the interest of a restricted group of social actors can lead to “hypocognition” (Lakoff, 2010), i.e. a simplistic framing that omits essential aspects to be considered for adaptation and sustainability. That is, the predominance of old perspectives due to elites remaining in power can lead to a lack of accountability (are they still valid?) and transparency (are they still justified?), hindering the process of adaptation in the holarchy according to new situations (is more growth desirable?). This is especially relevant in the current circumstances because of the supremacy of CE narratives in the decision-making process.

◊ Why is biosemiotics important in MuSIASEM?

Biosemiotics is relevant for MuSIASEM because it allows us to navigate among the epistemological troubles when representing SES across scales and dimensions: a good or bad explanation depends on the problems faced, making models and explanations not right or wrong but practical or useless. In this sense, the semiotic process has profound implications when using MuSIASEM. Humans represent only a shared perception of reality, not the actual reality, in their scientific analysis (Giampietro, 2003). When providing scientific evidence to guide policy, we must consider the implications of the pre-analytical choice of a given perspective. That is, any observer's point of view must be integrated into a more extensive knowledge process. The selection of models, data and monitoring that result in an agreement about the existence of "facts" used to guide specific actions result from the original choice of a given narrative relevant to addressing particular concerns. However, the priority given to different concerns (e.g. aspiration for economic growth or the need to preserve the environment) cannot be "scientifically justified". It simply reflects a normative decision, a product of a particular political and historical process. Consequently, any discussion over sustainability entails a political or ideological dimension that must be explicitly acknowledged and addressed in the pre-analytical phase. Consideration of different observers uncovering the existence of incommensurability of values (Munda, 2008), especially when modellers are part of the system and a semiotic process which is not external to power relations, turns MuSIASEM into a post-positivist approach that recognises pluralities of values and concerns[13].

Some papers illustrating with practical examples the relevance of the semiotic process when handling sustainability issues can be found when discussing the ethical, conflictive and relevant attributes associated with the process of milk production for different stakeholders (Giampietro and Bukkens, 2015); the political and epistemological implications of the representations of the resource nexus (Giampietro, 2018); or the different pre-analytical visions concerning the circular bioeconomy with different implications for sustainable growth (Giampietro, 2019b).

3.3.5. Dynamic Energy Budget.

◊ Main idea.

A social-economic system has to invest energy to obtain energy but also for other purposes, such as maintaining and updating social institutions.

◊ Theoretical background.

Herbert Spencer, one of the founding fathers of social science, correlated societal progress and energy surplus (McKinnon, 2010). The latter enabled social growth and, thereby, social differentiation. It also provided room for cultural activities beyond basic vital needs. Other eminent scholars such as Lotka (1922), Zipf (1941) and White (1943)

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[13] In practice, this means that the extent and grain of the observed system —macroscope, mesoscope and microscope in the jargon— as well as the observable attributes —the variables— must be selected according to the observer's concerns.

developed this idea from different fields. The concept of the dynamic energy budget for the study of social-economic systems is based on previous works in the field of system ecology. Analysing ecosystem structures, Ulanowicz (1986) found that the network of matter and energy flows conforming to an ecosystem can be divided into two functional parts: the hypercycle and the dissipative part. The first part has to provide the required energy supply (after considering local expenditure) to the rest of the system. The second has a purely dissipative nature and expresses activities that are net energy degraders. These two parts can be easily related to the two sides of a metabolic process: (i) the catabolic part (the one generating the hypercycle by destroying favourable gradients found in nature); and (ii) the anabolic part (the one expressing the activity of reproduction and control).

According to this conceptual distinction, the various functional compartments of a social-economic system can be divided between dissipative sectors, i.e. sectors involved intensively in the metabolism of biophysical flows and the use of exosomatic devices without producing either of them (e.g. service, government and the household sectors); and hypercyclic sectors, i.e. sectors which output more biophysical flows and exosomatic devices than they use for their own metabolism (e.g. the agricultural, energy, mining and industrial sectors). The strength of the hypercycle part, defined as the level of biophysical surplus generated per unit of human activity, determines the size and differentiation of activities that society can afford in the dissipative part (Giampietro et al., 2012). That is, there must be a balance between the energy and materials required to express the various societal functions (in all the constituent components of the society) and the supplied flow generated only by the hypercycle part. This implies a forced relation or dynamic equilibrium in the impredicative relations between what is achieved (a supplied flow of energy and materials generated by the hypercyclic compartments) and what is expected (a material standard of living determined by the aspirations of people living in society). In other words, external limits (associated with the concept of feasibility, i.e., environmental sources availability and sink carrying capacity) and internal limits (related to the idea of viability, i.e., the human, technological and institutional capacities) determine what is possible to happen, delimiting the realm of the political dispute (associated with the concept of desirability, i.e., hegemonic values and political contingencies). The consideration of fund and flow variables when characterising the metabolic identity of human societies implies that both variables act as constraints to the viability of this dynamic equilibrium. Both natural resources from the biosphere and human time and human-created goods from the technosphere are necessary to produce and consume goods and services, supporting the idea of “strong sustainability” (Couix, 2019).

◊ Why is the dynamic energy budget important in MuSIASEM?

The dynamic energy budget points out how societies depend on the quality of energy sources. However, post-industrial societies present a high specialisation in the service sector, with around 70% of the total paid work hours (Velasco-Fernández et al., 2020b). These societies rely on imports to compensate for their relatively low production in their hypercycle sectors in relation to their domestic consumption (Manfroni et al., 2021b). Therefore, externalisation must be considered and not only for energy issues to understand the factors allowing the expression of a given metabolic pattern. For instance, accounting for the externalised carbon emissions of the energy sector raises total GHG emissions of the sector by 60% on the EU average (Ripa et al., 2021), or the overall goods and services consumed in the EU involve the work of more than 130 million extra virtual workers (Pérez-Sánchez et al., 2021). In this sense, MuSIASEM enables consideration of the burdening shift that favourable terms of trade impose on other SES by providing a notional definition of a given set of production processes associated with a given quantity of imported commodities in relation to food and energy. These representations quantify end uses (secondary inputs and fund elements) and environmental pressures (primary flows and wastes) embodied in imports. Thus, for example, it would be possible to characterise domestic cereal production (from observed domestic supply systems) and imported cereal production (from virtual supply systems assessed with notional metabolic processors based on expected values from theoretical technical coefficients) to obtain a holistic view of biophysical requirements in the food sector. For examples of quantitative analysis considering externalisation, see Renner et al. (2020a) and Di Felice et al. (2024).

3.4. Conclusions.

The most complex challenges facing humanity in the 21st century, including climate change, biodiversity loss, peak oil and others (Heinberg, 2007), have to do with the existence of biophysical limits that seem to be incompatible with the aspirations of a growing population seeking better standards of living both in developed and developing countries. These limits (together with remaining poverty and inequality) affect the stability of the economic process or, in other words, the feasibility, viability and desirability of the different types of metabolic patterns expressed by different instances of social-economic systems. Dealing with these limits will require a total reconfiguration of our current material and energy use pattern, a radical change in socio-economic institutions and a re-adjustment of current social practices. However, despite the urgency of this need, most institutions and social actors remain in denial. The dominant reliance on CE narratives filters out this uncomfortable knowledge. As a result, the current unsustainability of the existing pattern of economic development is a subject carefully avoided because it represents a threat to the stability of hegemonic institutions. However, if one admits the existence of biophysical limits and the impossibility of maintaining the standard of living promised by consumerism, new perceptions and narratives are necessary for us to envision other societal configurations. The elaboration of a sound transformation pathway is not possible without new epistemic tools capable of (i) informing this deliberative process by checking the quality of different narratives on sustainable social practices and (ii) flagging the implausibility of many delusional technoscientific imaginaries.

The MuSIASEM methodology, in its more mature version, provides an accounting scheme to carry out a coherent analysis of the biophysical factors determining the sustainability of social-economic systems. Moreover, its main features —e.g. exploring the relations between environmental, social and economic systems, acknowledging incommensurable values, highlighting a strict focus on strong sustainability, including intangible elements (values, desires, narratives) when tackling sustainability crisis or stressing a biophysical reality with its laws and conditions— are faithful to critical aspects of ecological economics, especially to positions incompatible with CE (Melgar-Melgar and Hall, 2020). MuSIASEM's systemic and multidimensional perspective provides a superior framework, a much richer picture than CE limited by aggregate indicators based exclusively on monetary valuations, exploring burden-shifting and the inherent limits associated with the system under analysis on which to base complex policy decisions. In this way, the methodology shifts the focus from efficiency and optimality (for whom?) to a multidimensional representation based on a heterogeneous set of indicators showing the different trade-offs to be dealt with and the inevitable generation of winners and losers in sustainability issues. Moreover, using the flow-fund model allows a comparison between the size of the funds and flows operating inside the economic process and the size of the ecological funds and flows in the embedding environment on which the economic process depends. Therefore, MuSIASEM makes these relationships explicit and enables a robust sustainability analysis, pushing a change in perspective from a social-economic system to a social-ecological system.

Possible weaknesses in the methodology are basically associated with its performance. First, integrating different dimensions over different levels of analysis requires a significant amount of data. This information is not always readily available for all years and, when available, is not always produced with the same system categorisation. This entails extra work to re-arrange data that are generally available only indirectly. Transdisciplinary analysis requires disaggregated data that should be made publicly available. Second, the information space generated by MuSIASEM is highly dense. This entails adopting software to develop decision support tools to involve non-experts in the discussion. At this point, adopting clear transparency regarding the set of relations in the accounting phase should make this work of visualisation easy. Last but certainly not least, MuSIASEM can be used to check the plausibility of policies and the robustness of the scientific evidence characterising the expected future by identifying the metabolic characteristics of the holarchies, the strength of the hypercycles and the level of openness of the metabolic pattern. In the existing situation, this check has rarely generated pleasing results for the environment, flagging the existence of “uncomfortable knowledge” in existing sustainability discussions. That is, sustainability analyses based on MuSIASEM show the implausibility of proposed policies or sociotechnical imaginaries. For this reason, so far, applications of MuSIASEM have not been welcomed by either governments or private companies. The legitimacy of the establishment is based on claims that political choices are based on “scientific evidence”, even though, very often, what is used in actual decision-making processes is “policy-based evidence” (Marmot, 2004; Strassheim and Kettunen, 2014), i.e. model representations narrowly built to validate pre-defined targets.

Despite the potentialities mentioned above and the criticalities of MuSIASEM, its unconventional and transdisciplinary theoretical foundations represent a difficult challenge to most people approaching the methodology for the first time. Consequently, the lecture on specific case studies is highly recommended (see reference section). However, a synthetic and updated discussion of the most relevant and recent theoretical foundations was lacking, as well as to make the methodology more accessible to a broader audience. I have attempted to fill this gap in this chapter by introducing several examples to illustrate the main concepts and justify their relevance when approaching sustainability issues. In the next chapter, we will see how to apply the methodology from the ground up to a case study and what kind of reflections can arise.

3.5. Chapter references.

Ahl, V., Allen, T.F.H., 1996. Hierarchy Theory. Columbia University Press, New York.

Allen, T.F.H., Giampietro, M., 2014. Holons, creaons, genons, environs, in hierarchy theory: Where we have gone. Ecol. Modell. 293, 31–41. https://doi.org/10.1016/J.ECOLMODEL.2014.06.017

Allen, T.F.H., Starr, T., 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press, Chicago.

Barbieri, M., 2019. Code Biology, Peircean Biosemiotics, and Rosen's Relational Biology. Biol. Theory 14, 21–29. https://doi.org/10.1007/s13752-018-0312-z.

Berkes, F., Colding, J., Folke, C., 2003. Navigating Social-Ecological Systems : Building Resilience for Complexity and Change. Columbia University Press, New York.

Cabello, V., Renner, A., Giampietro, M., 2019. Relational analysis of the resource nexus in arid land crop production. Adv. Water Resour. 130, 258–269. https://doi.org/10.1016/j.advwatres.2019.06.014

Cadillo-Benalcazar, J.J., Giampietro, M., Bukkens, S.G.F., Strand, R., 2020a. Multi-scale integrated evaluation of the sustainability of large-scale use of alternative feeds in salmon aquaculture. J. Clean. Prod. 248, 119211. https://doi.org/10.1016/j.clepro.2019.119210

Cadillo-Benalcazar, J.J., Renner, A., 2020. Top-down and bottom-up vegetal and animal product metabolic profiles for 29 European countries (EU27 + United Kingdom + Norway) [dataset] [WWW Document]. Zenodo. https://doi.org/10.5281/ZENODO.3923010 (accessed 10 February 2022)

Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M., 2020b. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manage. 271, 110944. https://doi.org/10.1016/j.jenvman.2020.110944

Capra, F., 1996. The Web of Life: A New Synthesis of Mind and Matter. HarperCollins, London.

Cilliers, P., 1998. Complexity and postmodernism: Understanding complex systems. Routledge, London.

Couix, Q., 2020. Georgescu-Roegen's Flow-Fund Theory of Production in Retrospect. Ecol. Econ. 176, 106749. https://doi.org/10.1016/J.ECOLECON.2020.106749

Couix, Q., 2019. Natural resources in the theory of production: the Georgescu-Roegen/Daly versus Solow/Stiglitz controversity. Eur. J. Hist. Econ. Thought 26, 1341–1378. https://doi.org/10.1080/09672567.2019.1679210

Di Felice, L.J., 2020. Energy systems as holarchies: Complexity and sustainability across scales [dataset] [WWW Document]. Zenodo. https://doi.org/http://doi.org/10.5281/zenodo.4271325 (accessed 10 February 2022)

Di Felice, L.J., Pérez-Sánchez, L., Manfroni, M., Giampietro, M., 2024. Towards nexus thinking in energy systems modelling: A multi-scale, embodied perspective. Energy Policy 187, 114052. https://doi.org/10.1016/J.ENPOL.2024.114052

Di Felice, L.J., Ripa, M., Giampietro, M., 2019. An alternative to market-oriented energy models: Nexus patterns across hierarchical levels. Energy Policy 431–443.

https://doi.org/10.1016/j.enpol.2018.11.002

Emmeche, C., Kull, K. (eds.), 2011. Towards a Semiotic Biology: Life is the Action of Signs. Imperial College Press, London.

European Union Joint Research Center, 2010. International Reference Life Cycle Data System (ILCD) Handbook-General Guide for Life Cycle Assessment. European Union, Luxemburg.

Fischer-Kowalski, M., 1998. Society's Metabolism: The Intellectual History of Material Flow Analysis, Part 1, 1860-1970. J. Ind. Ecol. 2, 61–78. https://doi.org/10.1162/jiec.1998.2.1.61

Fischer-Kowalski, M., Haberl, H. (eds.), 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham.

Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age. Futures 25, 735–755.

Gell-Mann, M., 1994. The Quark and the Jaguar. Freeman, New York.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Gerber, J.F., Scheidel, A., 2018. In Search of Substantive Economics: Comparing Today's Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM. Ecol. Econ. 144, 186–194. https://doi.org/10.1016/j.ecolecon.2017.08.012

Giampietro, M., 2019a. The quality of scientific advice for policy: a few insights from complexity. Report produced in the context of the Horizon2020 project MAGIC, Grant Agreement No. 689669, 07 May 2019.

Giampietro, M., 2019b. On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. Ecol. Econ. 162, 143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001.

Giampietro, M., 2018. Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10, 1–17. https://doi.org/10.3390/su10072545

Giampietro, M., 2003. Multi-Scale Integrated Analysis of Agro-ecosystems. CRC Press, Boca Raton.

Giampietro, M., 1994. Using hierarchy theory to explore the concept of sustainable development. Futures 26, 616–625. https://doi.org/10.1016/0016-3287(94)90033-7

Giampietro, M., Allen, T.F.H., Mayumi, K., 2006. The epistemological predicament associated with purposive quantitative analysis. Ecol. Complex. 3, 307–327. https://doi.org/10.1016/j.ecocom.2007.02.005.

Giampietro, M., Aspinall, R.J., Ramos-Martín, J., Bukkens, S.G.F., 2014. Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use. Routledge, London.

Giampietro, M., Bukkens, S.G.F., 2022. Knowledge claims in European Union energy policies: Unknown knows and uncomfortable awareness. Energy Res. Soc. Sci. 91. https://doi.org/10.1016/j.erss.2022.102739

Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inform. 26, 18–28.

https://doi.org/10.1016/j.ecoinf.2014.07.007

Giampietro, M., Cadillo-Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez-Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliverable 4.4, 30 August 2020.

Giampietro, M., Mayumi, K., 2018. Unravelling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026

Giampietro, M., Mayumi, K., 2008. The Jevons Paradox: The Evolution of Complex Adaptive Systems and the Challenge for Scientific Analysis, in: Polimeni, J.M., Mayumi, K., Giampietro, M., Alcott, B. (Eds.), The Jevons Paradox and the Myth of Resource Efficiency Improvements. Earthscan Research Edition, London, p. 200.

Giampietro, M., Mayumi, K., 2000a. Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. Popul. Environ. 22, 155–210. https://doi.org/10.1023/A:1026643707370

Giampietro, M., Mayumi, K., 2000b. Multiple-scale integrated assessment of societal metabolism: introducing the approach. Popul. Environ. 22, 109–153. https://doi.org/10.1023/A:1026691623300

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London.

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Societies : Where Economists Fall Short. Routledge, London.

Giampietro, M., Renner, A., 2020. The Generation of Meaning and preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria, in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

González-López, R., Giampietro, M., 2018. Relational analysis of the oil and gas sector of Mexico: Implications for Mexico's energy reform. Energy 154, 403–414. https://doi.org/10.1016/j.energy.2018.04.134

González de Molina, M., Soto Fernández, D., Guzmán Casado, G.I., Infante Amate, J., Aguilera Fernández, E., Vila Traver, R., García Ruiz, R., 2019. Historia de la agricultura española desde una perspectiva biofísica 1900-2010. Gobierno de España. Ministerio de Agricultura, Pesca y Alimentación, Madrid.

Heinberg, R., 2007. Peak everything: walking up to the century of declines. New Society Publishers, Gabriola Island, British Columbia, Canada.

Holland, J.H., 2006. Studying complex adaptive systems. J. Syst. Sci. Complex 19, 1–8. https://doi.org/10.1007/s11424-006-0001-z

Holland, J.H., 1995. Hidden Order: How Adaptation Builds Complexity. Perseus Books, New

York.

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.

Infante Amate, J., González de Molina, M., Toledo, V.M., 2017. El metabolismo social. Historia, métodos y principales aportaciones. Rev. Iberoam. Econ. Ecológica 27, 130–152.

Koestler, A., 1967. The Ghost in the Machine. Macmillan Co., New York.

Kull, K., Deacon, T., Emmeche, C., Hoffmeyer, J., Stjernfelt, F., 2009. Theses on biosemiotics: Prolegomena to a theoretical biology. Biol. Theory 4, 167–173. https://doi.org/10.1162/biot.2009.4.2.167

Lakoff, G., 2010. Why it matters how we frame the environment. Environ. Commun. A J. Nat. Cult. 4, 70–81. https://doi.org/10.1080/17524030903529749.

Larrabeiti-Rodríguez, J.J., Velasco-Fernández, R., 2022. Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) revisited: synthesizing and updating the theoretical foundations. J. Crit. Econ. 34, 44–68.

Lotka, A.J., 1922. Contribution to the energetics of evolution. Proc. Natl. Acad. Sci. 8, 147–151. https://doi.org/10.1073/pnas.8.6.147.

Louie, H.A., 2017. Intangible Life: Functional Connections In Relational Biology. Springer International, Cham.

Luhmann, N., 1995. Social Systems. Stanford University Press, Stanford.

Manfroni, M., Bukkens, S.G.F., Giampietro, M., 2021a. The declining performance of the oil sector: Implications for global climate change mitigation. Appl. Energy 298, 117210. https://doi.org/10.1016/J.APENERGY.2021.117210

Manfroni, M., Velasco-Fernández, R., Pérez-Sánchez, L., Bukkens, S.G.F., Giampietro, M., 2021b. The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth. Ecol. Econ. 190, 107183. https://doi.org/10.1016/J.ECOLECON.2021.107183

Marcos-Valls, A., Kovacic, Z., Giampietro, M., Kallis, G., Rieradevall, J., 2020. Isolated yet open: A metabolic analysis of Menorca. Sci. Total Environ. 738, 139221. https://doi.org/10.1016/j.scitotenv.2020.139221

Marmot, M.G., 2004. Evidence based policy or policy based evidence? BMJ 329, 906–907. https://doi.org/10.1136/bmj.328.7445.906

Martin, N., Talens-Peiró, L., Villalba-Méndez, G., Nebot-Medina, R., Madrid-López, C., 2023. An energy future beyond climate neutrality: Comprehensive evaluations of transition pathways. Appl. Energy 331, 120366. https://doi.org/10.1016/J.APENERGY.2022.120366

Martinez-Alier, J., Munda, G., O'Neill, J., 1998. Weak comparability of values as a foundation for Ecological Economics. Ecol. Econ. 26, 277–286.

Maturana, H.R., Varela, F.J., 1980. Autopoiesis and Cognition: The Realization of the Living. D. Reidel Publishing, Dordrecht.

McKinnon, A., 2010. Energy and society: Herbert Spencer's "energetic sociology" of social evolution and beyond. J. Class. Sociol. 10, 439–455.

https://doi.org/10.1177/1468795X10385184.

Melgar-Melgar, R.E., Hall, C.A.S., 2020. Why ecological economics needs to return to its roots: The biophysical foundation of socio-economic systems. Ecol. Econ. 169, 106567. https://doi.org/10.1016/j.ecolecon.2019.106567

Munda, G., 2008. Social Multi-Criteria Evaluation for a Sustainable Economy. Springer, Berlin.

Nicolis, G., Prigogine, I., 1977. Self-Organization in Nonequilibrium Systems. Wiley, New York.

Odum, H.T., 1971. Environment, Power and Society. Wiley-Interscience, New York.

Pattee, H.H., 1995. Evolving self-reference: Matter, symbols and semantic closure. Commun. Cogn. Intell. 12, 9–27.

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., Ripa, M., 2019. Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. Energy Policy 124, 13–22. https://doi.org/10.1016/j.enpol.2018.09.028

Pérez-Sánchez, L., Velasco-Fernández, R., Giampietro, M., 2021. The international division of labor and embodied working time in trade for the US, the EU and China. Ecol. Econ. 180, 106909. https://doi.org/10.1016/j.ecolecon.2020.106909

Pirgmaier, E., Steinberger, J.K., 2019. Roots, riots and radical change-a road less travelled for ecological economics. Sustainability 11. https://doi.org/10.3390/su11072001

Prigogine, I., 1961. Introduction to thermodynamics of irreversible processes. Interscience Publishers, New York.

Prigogine, I., Glansdorff, P., 1971. Thermodynamic Theory of Structure, Stability and Fluctuation. Wiley, New York.

Rashevsky, N., 1935. Mathematical Biophysics. Nature 135, 528–530. https://doi.org/10.1038/135528a0

Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M., 2020a. Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosyst. Serv. 46, 101195. https://doi.org/10.1016/j.ecoser.2020.101195

Renner, A., Louie, H.A., Giampietro, M., 2020b. Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity., in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

Ripa, M., Di Felice, L.J., Giampietro, M., 2021. The energy metabolism of post-industrial economies. A framework to account for externalization across scales. Energy 214, 118943. https://doi.org/10.1016/j.energy.2020.118943

Rittel, H.W., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169. https://doi.org/10.1007/BF01405730

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol. Soc. 14. https://doi.org/10.5751/ES-03180-140232

Rosen, R., 2005. Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of

Life. Columbia University Press, New York.

Rosen, R., 2000. Essays on Life Itself. Columbia University Press, New York.

Schrödinger, E., 1967. What is Life? Mind and Matter. Cambridge University Press, Cambridge.

Scott, I., Gong, T., 2021. Coordinating government silos: challenges and opportunities. Glob. Public Policy Gov. 1, 20–38. https://doi.org/10.1007/S43508-021-00004-Z/TABLES/2

Shove, E., Pantzar, M., Watson, M., 2012. The dynamics of social practice : everyday life and how it changes. SAGE, London.

Simon, H.A., 1962. The Architecture of Complexity: Hierarchic Systems. Proc. Am. Philos. Soc. 106, 467–482. https://doi.org/10.2307/985254

Spash, C.L., 2020. A tale of three paradigms: Realising the revolutionary potential of ecological economics. Ecol. Econ. 169, 106518. https://doi.org/10.1016/j.ecolecon.2019.106518

Spash, C.L., 2015. The content, direction and philosophy of ecological economics, in: Martinez-Alier, J., Muradian, R. (Eds.), Handbook of Ecological Economics. Edward Elgar, Cheltenham, pp. 26–47. https://doi.org/10.4337/9781783471416.00006

Strassheim, H., Kettunen, P., 2014. When does evidence-based policy turn into policy-based evidence? Configurations, contexts and mechanisms. Evid. Policy A J. Res. Debate Pract. 10, 259–277. https://doi.org/10.1332/174426514X13990433991320

Ulanowicz, R.E., 1986. Growth and Development: Ecosystem Phenomenology. Springer-Verlag, New York.

Velasco-Fernández, R., Dunlop, T., Giampietro, M., 2020a. Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy. Energy Policy 137. https://doi.org/10.1016/j.enpol.2019.111089

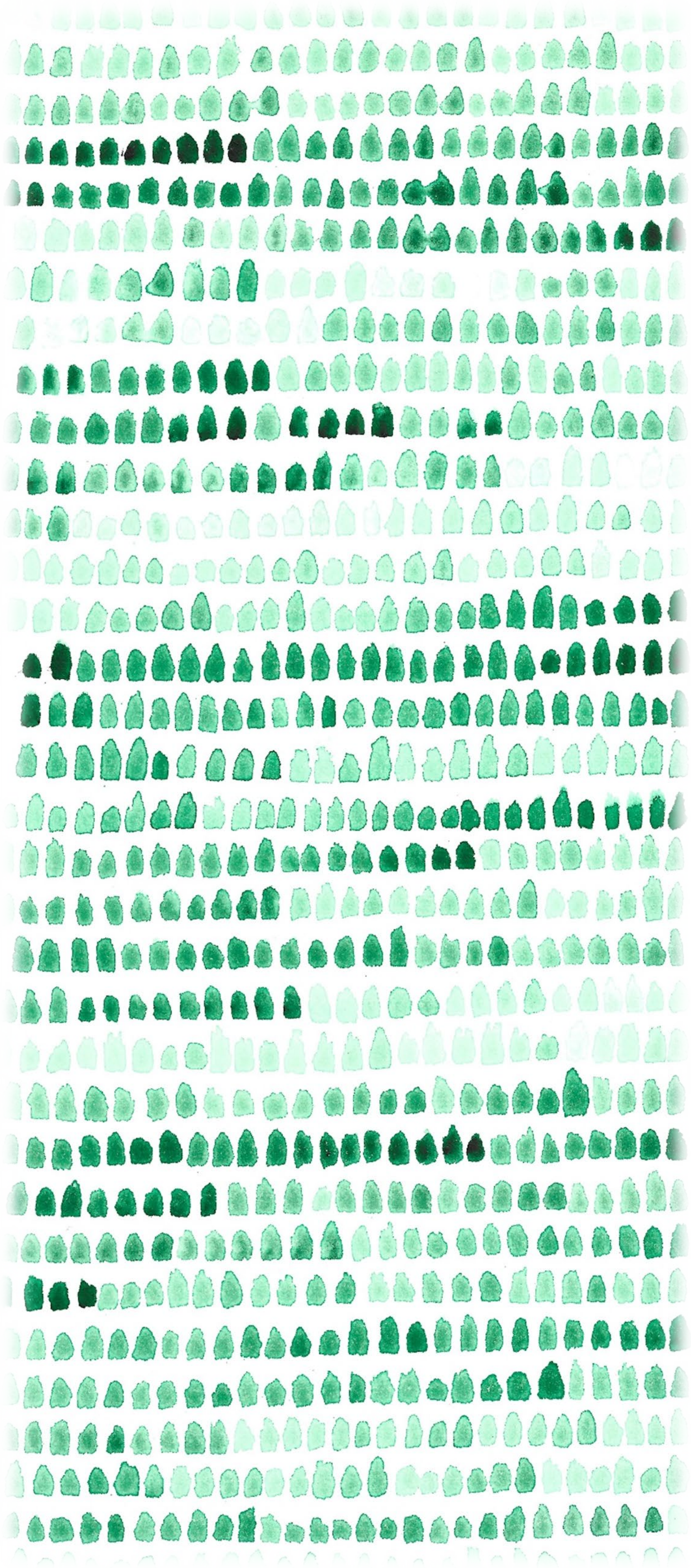
Velasco-Fernández, R., Pérez-Sánchez, L., Chen, L., Giampietro, M., 2020b. A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. Energy Strateg. Rev. 32, 100562. https://doi.org/10.1016/j.esr.2020.100562

Weitz, N., Carlsen, H., Nilsson, M., Skånberg, K., 2018. Towards systemic and contextual priority setting for implementing the 2030 agenda. Sustain. Sci. 13, 531–548. https://doi.org/10.1007/s11625-017-0470-0

White, L.A., 1943. Energy and the evolution of culture. Am. Anthropol. 45, 335–356.

Zipf, G.K., 1941. National Unity and Disunity: The Nation as a Biosocial Organism. Principia Press, Bloomington, IN.

Chapter 4



4. The metabolic pattern of Andorra: a diagnosis.

"Contempla el jove feixes i boscatges
i, darrere els pradells de la Regina,
una esmaragda en forma de petxina,
tota plena de perles i de flors:
és la vall delitosa de Setúria;
quan amb son bes primer l'alba l'arrosa
sembla l'àurea conquilla en què flairosa
del mar isqué la reina dels amors".
Jacint Verdaguer[*].

4.1. Introduction.

The Principality of Andorra, a small, mountainous country in the Pyrenees (Figure 4.1), is not divorced from the reality contextualised in Chapter 1.

Figure 4.1. Geographical location of Andorra. Source: Google Maps.

The country has undergone during the twentieth century a dramatic transformation from a rural economy of subsistence to an urban economy specialised in the service sector, mainly in tourism and financial activities, embedded in global flows of

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[*] Extract from the epic poem *Canigó (Cant IV, Lo Pirineu, Tall 26)* whose original version dates to 1886. Verdaguer i Santaló, J. (2022). *Poemes llargs. Teatre. Totes les obres, II (Canigó)*. Proa, Barcelona.

capital and people (Lluelles and García, 2018). As a mountain area, the country is vulnerable to climate change (IPCC, 2007) but, at the same time, contributes to the generation of local and global environmental pressures with the intensification of tourist activities. The improvement of mobility and communication technologies in the last decades has increased the number of permanent and temporary residents, tourists and seasonal workers, resulting in an overall increase in the consumption of food, energy, water, and other material flows. The country now has a high population density and an intense pace of metabolic transformations.

Andorra, as a member of The United Nations (UN), acceded to the United Nations Framework Convention on Climate Change (UNFCCC) as a non-Annex I Party on the 2nd March 2011 and is therefore subject to specific obligations concerning environmental policies (Miquel et al., 2021). Additionally, the Andorran Government presented the project "*Projecte de llei de la transició energètica i el canvi climatic*" (2018), which the *Consell General* passed as "*Llei 21/2018 del 13 de setembre, d'impuls de la transició energètica i del canvi climatic*" (Litecc)[14] (BOPA, 2018). This law lays the foundations for more sustainable development under the narrative of achieving greater energy sovereignty and moving towards a carbon-neutral society. The main objectives it raises are:

- Reducing energy intensity (measured in TOE/M€ of GDP[15]) by at least 20% in 2030 and 30% in 2050 compared to the base year 2010.
- Reducing annual greenhouse gas emissions compared to a "business as usual" scenario by at least 37% in 2030.
- Increasing national electricity production to at least 33% of the demand by 2030 and 50% by 2050.
- Ensuring that at least 75% of energy from renewable sources is used in national electricity production.
- Increasing the percentage of electric vehicles in the national vehicle fleet to 20% by 2030 and 50% by 2050.

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[14] Available on the website of the *Consell General*: https://www.consellgeneral.ad/ca/arxiu/arxiu-de-lleis-i-textos-aprovats-en-legislatures-anteriors/vii-legislatura-2015-2019/copy_of_lleis-aprovades/llei-21-2018-d2019impuls-de-la-transicio-energetica-i-del-canvi-climatic-litecc

[15] Tonnes of oil equivalent per million euros of gross domestic product.

- Halving emissions from the domestic transport sector.

However, we should acknowledge that when discussing sustainable development, there are no optimal or win-win solutions (Velasco-Fernández, 2020). Plans for rapid decarbonisation of the economy generally reflect superficial visions based on the adoption of a single scale (the country as a whole) and a single dimension of analysis (the use of exosomatic energy, i.e., energy carriers used outside the human body), where other relevant aspects of the sustainability discussion are systematically ignored. In fact, a decarbonisation policy of the economy should consider other environmental challenges, such as water scarcity, land displacement or waste generation, that require integrating information from different dimensions (Nilsson et al., 2016). Moreover, it is necessary to emphasise the existence of tensions between different concerns, such as the aspiration for economic growth and the need to preserve the environment (Giampietro, 2019). As a result, robust knowledge claims based on a biophysical and systemic approach are often removed from the discussion concerning sustainability plans. This is why, before embarking on plans for sustainability, a baseline of biophysical indicators is needed (Melgar-Melgar and Hall, 2020).

To facilitate this biophysical approach, we understand Andorra as a dissipative structure (Nicolis and Prigogine, 1977) capable of reproducing and adapting a network of structural and functional elements associated with its identity and want to study its metabolism. This analysis enables a multidimensional characterisation linked to a nexus approach. The concept of the nexus (often short for water-energy-food-environment, or WEFE, nexus) has emerged over the past 15 years as a robust framework for understanding the relationships and critiquing established distinctions between categories of environmental governance that have traditionally been managed in separation (D'Odorico et al., 2018; Williams et al., 2019). The characterisation of the nexus will follow the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach developed by Giampietro et al. (2000a, 2000b) at the Institute of Environmental Science and Technology (ICTA). The MuSIASEM approach has been consolidated as a theoretical and methodological framework that integrates environmental, social, and economic information. MuSIASEM allows us to identify and characterise the expected entanglement relations between the observed nexus flows within the metabolic pattern of SES (Giampietro, 2018). That is, a multiscale analysis of the metabolic pattern comprehends the various conversion processes of energy and materials inputs needed to reproduce the structural elements, that combined in functional elements, express the expected functions of the system under analysis.

The characterisation of the metabolic pattern of Andorra is the cornerstone of this chapter. This diagnosis effectively captures the emergent competition among various functional elements of the Andorran society for limited resources such as water, land, or energy. It also enhances our understanding of the complex interrelations and tensions between social, economic and environmental goals. Additionally, it offers valuable insights into Andorra's position within the broader context of globalisation, uneven geographical development, climate change, and resource depletion. These insights can serve as a basis for discussing sustainable solutions and their implementations.

This chapter is structured as follows: the next section contextualises the Andorra case study. Section 4.3 describes the different methodological stages of implementation, the main data sources, and limitations. Section 4.4 presents and discusses the results. Section 4.5 compares these results with those of Spain and France and the average of the EU. In section 4.6, the metabolic profile obtained for Andorra is contrasted to that of the island of Menorca, another area of high tourism specialisation. The chapter closes with some conclusions.

4.2. Contextualization.

Andorra is a small and mountainous country between France and Spain in the Pyrenees Mountains, with approximately 77 000 inhabitants in 2019 (Department of Statistics, 2019a). The evolution of the population has been exponential in the country. In 1947, Andorra had only 5 385 inhabitants (Figure 4.2). Rapid economic development and high immigration rates in the second half of the 20th century explain this increase (Miquel et al., 2014). Moreover, Andorra is one of the few countries in the world where the population with Andorran nationality (48.7%) is smaller than the population of residents with non-Andorran nationality (51.3%) (CRES, 2018).

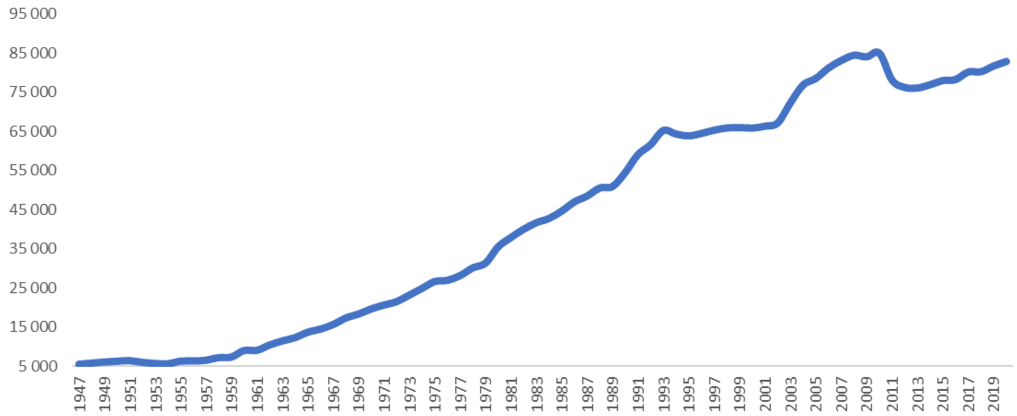


Figure 4.2. Evolution of the registered population in Andorra. Source: Department of Statistics (2019).

The country has an area of 468 rugged km^2 and an average height of 2 044 metres. About 70% of the territory is covered by forest and rocky surfaces, while infrastructure and urban areas account for only 3% (Miquel et al., 2021). The rest of the country includes meadows, farmland, and inland waters (Figure 4.3). Agriculture activities are also mainly found in the valleys. Based on a traditional farming management system, the agricultural sector is vital in providing many environmental services, particularly in landscape conservation (Komac et al., 2020).

The industrial sector remains limited, representing 3.4% of GDP in 2019. The Andorran economy is mainly focused on tertiary activities. Services is the most critical sector of the Principality's economy, regarding 86.1% of the country's business and 87.7% of the employees. Thus, tourism is one of the fundamental pillars of the Andorran economy, directly or indirectly responsible for 85% of GDP, with about 8 million visitors per year. In winter, services related to skiing are predominant, with 2.5 million skiing days sold (2017-2018 season) distributed over more than 3 200 ha of skiing surface. The snow sector is the pillar of 2 000 workplaces but is very vulnerable to climate change and the rise of hydrocarbon prices, given that road networks are the only link with neighbouring countries (Miquel et al., 2021). Generally, the country enjoys a high material standard of living and is positioned 34th in the ranking of countries according to their GDP per capita (World Bank, 20019). It also has an HDI value of 0.858, which puts the country in the "very high" human development classification, setting Andorra at 40 out of 191 countries and territories (UNDP, 2019).

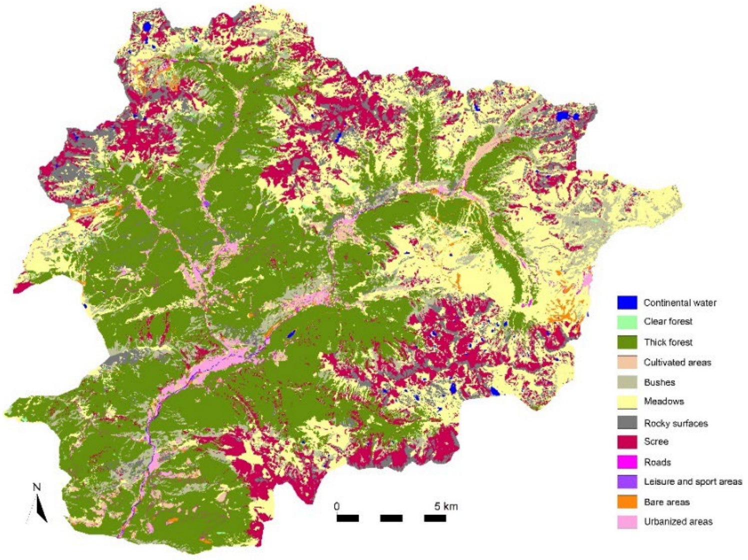


Figure 4.3. Map of land covers. Source: Cenma-IEA (2012a).

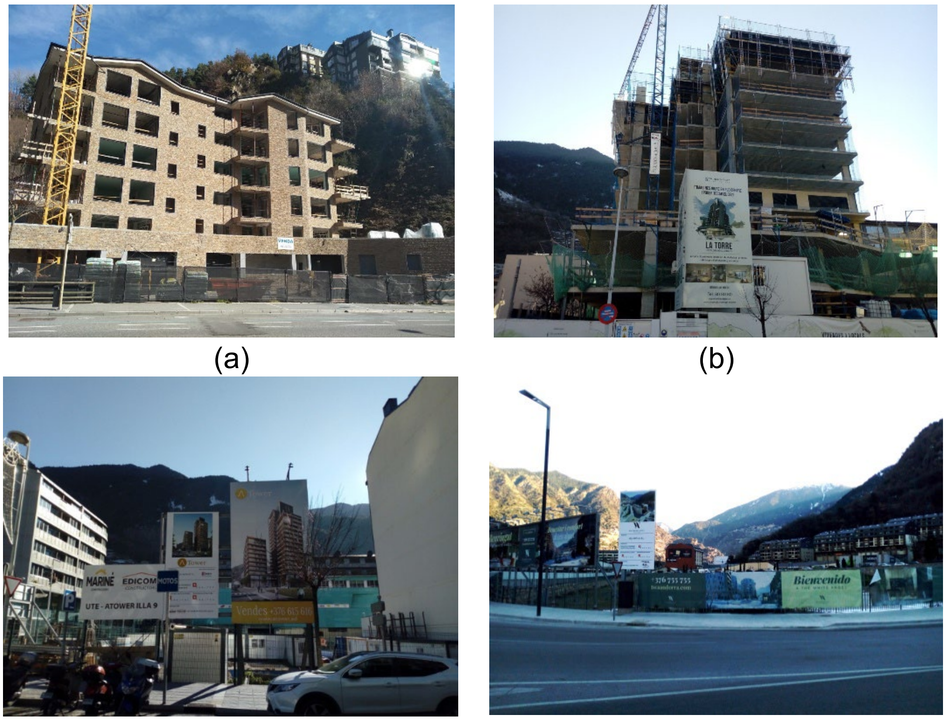
To diversify the economy, Andorra is trying to boost foreign investment (Andorra Business, 2023). As a result, the production of urban space (Harvey, 2019) has become an essential source of capital accumulation (Figure 4.4). These economic activities inevitably generate environmental pressures that can result in a lack of system sustainability. For this reason, several studies have been launched to determine the maximum growth capacity of the different urban areas (BOPA, 2023).

4.3. MuSIASEM applied to Andorra.

The MuSIASEM accounting framework builds on various pre-analytical steps, as synthesised in Table 3.2 of the previous chapter. The following points summarise the application of this methodology to Andorra, providing a step-by-step guide that bridges the gap between methodology and practice. This section also details the data used in the analysis and highlights certain limitations.

◊ *Step 1: Definition of a social-economic system as a set of hierarchically organised functional compartments (made up of structural elements) embedded in a natural system.*

A system is a set of elements that expresses meaningful interactions. In the case of sustainability analysis, we study the interactions of SES on the inside (the parts generating the emergent property of the whole) and on the outside (the whole is viewed as a black box within its context).



(a) (b)

(c) (d)

Figure 4.4. Production of new urban space in Andorra. A new building is in a former pasture area in La Massana (a). New towers projected or under construction in Andorra la Vella (b,c,d) are now —2024— a reality. Source: Own elaboration.

The expression of a metabolic pattern must be desirable for the people living in that system and, when needed, should be adapted to new boundary conditions (changes on the outside) or new aspirations (changes on the inside). At the same time, the metabolic pattern must be compatible with its environment. Therefore, a SES is a set of constituent components (a set of parts represented by a combination of structural and functional elements) that preserve and adapt the identity of the whole in time because of their coordinated interactions. This entails maintaining the identity of (i) its structural elements, (ii) its functional elements, and (iii) the set of relations over the characteristics of the structural and functional elements expressing the emergent property of the whole (Giampietro and Renner, 2020). In this way, we must first define the overall system at level N (defining a system's identity entails a pre-analytical choice of the system's boundaries). Then, within this functional whole, we can identify a set of lower-level functional compartments at level (N-1) (e.g. household sector, paid work sector) based on the functions expressed in society (e.g. reproducing human labour, generation of income). These lower-level compartments can be further subdivided (levels N-2, N-3, etc.) into other functional/structural elements. In this way, when dealing with social-economic systems that have been self-organising for centuries, it is relatively easy to define both the whole system and the parts as a compartmentalisation of the functional and structural elements is already available in the representation given by their statistical offices where the whole country is divided into economic sectors, which are further divided into sub-sectors and then into different groups of activities.

Initially, the following functional compartments and sub-compartments (i.e. what we called constituent components in Chapter 3) will be considered for the study of the Andorran system: the whole (N), the paid work sector (PW, N-1) and the household sector (HH, N-1). Within the PW compartment, we define three economic sectors at level N-2: (i) the agricultural sector (AG), including agriculture, livestock and fish farming; (ii) the industrial sector (ICM), including the energy, industry, construction and manufacturing activities; and (iii) the service sector (SG), including services and government activities.

Transportation is another functional sector that must be adequately defined. As a functional compartment, it includes human activity in the HH (using private cars and motorcycles) and the PW (including collective and freight transport services). In this study, starting from the data of Travesset-Baro (2017), energy consumption in transport has been assigned to the HH and PW, discounting the item corresponding to fuel tourism, i.e. the fuels purchased by tourists and same-day visitors when shopping in Andorra is not included in the different functional requirements.

◊ *Step 2: Definition of the metabolic components (i.e. the fund elements) over the functional compartments of the system.*

This step involves selecting relevant fund elements and their allocation to the various functional compartments of the system. In the MuSIASEM approach, human activity (HA) and land use (LU) are considered fund elements to characterise the constituent components of the system studied. HA (measured in hours) is the critical fund element for socioeconomic analysis. Using hours of human activity allocated to different categories of social practices allows us to characterise and quantify the diversity of activities carried out within a social-economic system. In particular, it will enable the distinction between activities of the paid work sector (where typologies of human activity are described as economic jobs) from other activities done at home or outside the labour market (where typologies of human activities are defined as specific forms of social practices).

LU (measured in hectares) is also a vital dimension of the analysis, as land represents the fund that refers to the environment and ecosystem uses in the study area. Both categories, depicted in Figure 4.5, are used to measure the size of the functional compartments and sub-compartments, respecting the congruence constraint of “closure” over the different hierarchical levels of analysis, i.e. the sum of the size of the fund elements described at the given level N must be equal to the sum of the size of all fund elements described at the level N-1 and so on.

Data about LU for this study has been extracted from the latest land use map of Andorra (CENMA-IEA, 2012b). Percentages calculated from the “authorised area” data (Department of Statistics, 2019b) have been applied to disaggregate the information from the land cover map between the different functional compartments (see Appendix A for more information about how the numbers have been produced). Data about HA, expressed in hours per year, has been calculated by summing (i) the activity of the permanent residents, (ii) the activity of temporary and cross-border workers, and (iii) the activity of tourists (staying overnight) and same-day visitors.

This consideration concerning HA is necessary for adequately characterising an open system such as Andorra in which the characteristics of the flows (money, energy, water, food) do not depend only on the activities expressed by the permanent residents. The equivalent population was calculated according to the Andorran Government (2016a)[16]. The data about HA in paid work (i.e. number of jobs multiplied per hours of workload) is based on the information presented in CRES (2018). The calculation considers all contracts full-time with an annual maximum of 1 800 hours worked following the *Codi de Relacions Laborals* (BOPA, 2009). The extra hours per year have also been included in the assessment. This assessment underestimates the number of hours worked because (i) a certain amount of informal work is not considered (Iglesias-Pérez et al., 2018); (ii) there is a high degree of precarious employment in economies based on the tourism sector (Cañada, 2018); and (iii) the work carried out by foreign companies in Andorra has not been considered.

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[16] Using this formula:
Equivalent Population=Resident population+ 0.4*Frontier Workers+180/365*Seasonal Workers +0.4/365*Hikers+1/365*Nights spent by tourists.

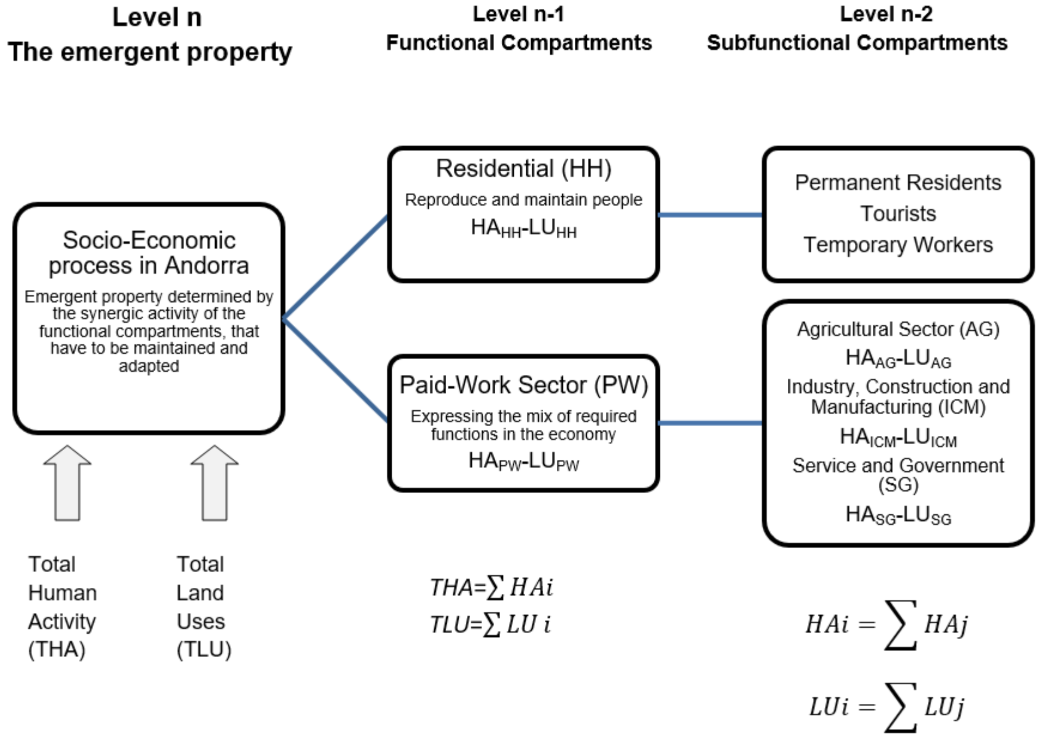


Figure 4.5. Hierarchical organisation of the levels in the Andorran system. Source: Own elaboration.

The categories defined in Figure 4.5 refer only to social-economic processes in Andorra. About the presence of ecological funds (e.g. forests, meadows, aquatic ecosystems), their self-organisation activities are outside human control. However, since their services are needed, their size and activity must be considered. The analysis of these funds is essential to assess environmental impacts. In this study, the size of ecological funds is mapped in terms of “non-managed land” (NML). This category includes land covers, such as forests, rocky areas or rivers, that supply environmental services that people in Andorra can use but whose characteristics do not depend directly on human intervention (even though they may be affected by it). The activities of these ecological funds may significantly affect the quality of life of the people of Andorra (e.g. carbon sinks, water cycle, aesthetic aspects and cultural identity) as well as economic sectors, such as tourism.

◊ *Step 3: Definition of the various flow elements (e.g. energy, water, money) used by the selected fund elements.*

MuSIASEM connects funds (the agents and transformers of flows inside a process) and flows (the elements that are utilised and dissipated) inside the metabolic pattern across different levels of analysis. In this chapter, six flow elements have been considered:

electricity (E, in GWh), electricity in thermal equivalent (E T.E.., in TJ), fuel (F, in TJ) and processed heat (H, in TJ) —as energy carriers; energy throughput expressed in gross energy requirement (GER); and cubic meters of blue water (keeping the distinction between consumptive and non-consumptive use). To establish a bridge between biophysical and monetary variables, accounting for the flows of the gross value added (GVA) of economic sectors has also been examined. Moreover, assessing GHG emissions associated with the different functional compartments and quantifying the waste generated at level N have been contemplated.

◊ *Step 4: Definition of metabolic characteristics assessing metabolic pressure and performance.*

The methodology uses intensive and extensive variables that effectively diagnose the requirements of the nexus biophysical flows, guaranteeing the system's survival and reproduction. The specific flow/fund ratios calculated at different levels of analysis are the intensive variables, characterising qualitative aspects, i.e. the metabolic performance of the fund elements. Examples of flow/fund ratios are the exosomatic metabolic rate (EMR), measured in MJ per hour (MJ/h), characterising the exosomatic energy consumption per hour of human activity in each functional compartment; the water metabolic density (WMD), measured in cubic meters per hectare (m^3/ha), characterising the water consumed per hectare in each functional compartment; or the economic labour productivity (ELP) which reports on added value generated per hour worked (€/h). Conversely, the size of societal compartments, providing information on the structural relation between the functional parts and the whole, and different types of resource requirements, i.e. the metabolic pressure, are based on extensive variables.

As noticed earlier, this accounting system defines constituent components as mutually exclusive, serving as a budget that sets limits on the economy. This means that extensive variables describing their size must maintain closure across different levels of analysis. This issue determines a forced set of metabolic relations over the size of the constituent components and their metabolic pace through different hierarchical levels. For example, Equation 1 shows the total energy requirements, i.e. the total energy throughput (TET), as a product of an extensive and intensive variable at level N, i.e. the total human activity (THA) and the exosomatic metabolic rate (EMR). This value must match when multiplying the variables corresponding to the hierarchical level N-1, as Equation 2 reveals. Therefore, the metabolic energy requirements of the society as a whole (level N) depend on four distinct factors that can only be observed at the level N-

1: the human activity of the household sector and the paid work sector (HA_{HH} and HA_{PW}) and the pace of energy metabolism in the household sector and the paid work sector (EMR_{HH} and EMR_{PW}).

$$TET_{level\ N} = THA_{Level\ N} \cdot EMR_{Level\ N} \quad (1)$$

$$(TET)_{Level\ N} = [HA_{HH} \cdot EMR_{HH}]_{Level\ N-1} + [HA_{PW} \cdot EMR_{PW}]_{Level\ N-1} \quad (2)$$

In this chapter, the following intensive variables have been established: (i) exosomatic metabolic rate (EMR) per unit of human activity; (ii) exosomatic metabolic density (EMD) per unit of land use; (iii) water metabolic rate (WMR) per unit of human activity; (iv) and water metabolic density (WMD) per unit of land use. The intensive variables of economic labour productivity (ELP) and economic land use productivity (ELUP) have also been considered in relation to the metabolic characteristics of economic productivity.

◊ *Step 5: Data gathering.*

As we saw in Chapter 3, MuSIASEM allows the combining of top-down and bottom-up strategies to gather data. Top-down strategies use statistical data to characterise the metabolic characteristics of the components of the system; for instance, the gross energy requirement for the maintenance of household activities divided by the hours of human activity devoted to residential activities provided a benchmark for the metabolic rate in the residential sector. Bottom-up strategies use benchmarks for specific types of structural elements (e.g. individual households) that can be scaled up to explain the metabolic characteristics of the components. Thus, if we know the characteristics of different typologies of households, their different energy metabolic requirements and size, we can estimate the total amount of energy used in the HH sector in a certain period by scaling up the results obtained for each type.

The methodology applied in this chapter has been primarily based on a top-down approach. However, a bottom-up analysis based on Travesset-Baro (2017) has been used to analyse the HH's energy requirements at level N-2. Table 4.1 summarises the variables considered and data sources.

Table 4.1. Extensive and intensive attributes and sources used in Chapter 4.

	External Attribute	Definition and units	Sources
	Fund elements used to assess the size of constituent components		
	HA (Human activity)	Time in, in hours (h) devoted to each level of analysis	-CRES (2018) -Andorra Government (2016a) -Department of Statistics (2019a)
	LU (Land use)	Area, in hectares (ha), devoted to each level of analysis	-CENMA-IEA (2012b) -Department of Statistics (2019b)
	Flow elements used to assess the metabolic pace of constituent components		
Extensive Variables	GVA (Gross value added)	Value, in EUR millions (M€) of goods and services produced in each level of analysis	-Department of Statistics (2019c)
	Ec (Energy carrier)	Amount of every type of energy used in each level of analysis (GWh for electricity and TJ for thermal energy and liquid fuels) Types of energy considered: (i) electricity (E); (ii) fossil fuels used as fuel (F) and fossil fuels used for heating (H)	-Travesset-Baro (2017) -Department of Statistics (2019d)
	GER (Gross energy requirement)	Equivalence in TJ for E (value multiplied by 2.61), F (value multiplied by 1.38) and H (value multiplied by 1.10) Assuming that fossil energy is used to produce the different energy carriers (Partial Substitution Method)	-Giampietro et al. (2013)
	WT (Water throughput)	Amount of blue water used in each level of analysis (m^3)	-Andorran Government (2016b)
	GHG emissions	Amount of CO_2 eq. emissions for the type of energy used in each level of analysis Types of energy considered: (i) electricity (E); (ii) fossil fuel used as fuel (F) and fossil fuel used for heating (H)	-Miquel et al. (2021) -Travesset-Baro (2017)
	SW (Solid waste)	Amount of solid waste generated for the whole of the social-ecological system under analysis	-Andorran Government (2016a)
	Metabolic characteristics in relation to dissipation		
Intensive Variables	MR (Metabolic rate)	Flow/HA: Amount of flow (Ec, GER or WT) per unit of human activity (HA) devoted to each level of analysis (unit/h)	
	MD (Metabolic density)	Flow/LU: Amount of flow (Ec, GER or WT) per unit of land use (LU) devoted to each level of analysis (unit/ha)	
	Metabolic characteristics in relation to productivity		
Intensive Variables	ELP (Economic labour productivity)	GVA/HA: Gross value added (in nominal terms) per hour of human activity in each level of analysis (€/h)	
	ELUP (Economic land use productivity)	GVA/LU: Gross value added (in nominal terms) per hectare of land use in each level of analysis (€/ha)	

4.4. Results and discussion.

This section presents and discusses the diagnostic results of the analysis of Andorra's metabolic pattern. As explained in Chapter 3, the metabolic pattern is characterised by using an end-use matrix (EUM) and an environmental pressure matrix (EPM). The EUM obtains a quantitative representation of how the different secondary inputs, such as energy carriers or distributed water, are metabolised by the funds under human control inside the technosphere to perform the various functions required to maintain the system. The EPM tracks the supply of primary flows (generated by processes outside human control) and the generation of primary wastes associated with using the secondary inputs metabolised in the EUM. The focus of the analysis of this chapter has been to develop an internal EUM for energy and water and an internal EPM (referring to the primary flows observed in the boundaries of Andorra) for GHG emissions and wastes. Rows in the matrices show the different hierarchical levels of analysis, and columns show the various observable attributes considered. Note that the rounding of significant digits might sometimes modify the sum along columns.

4.4.1. The end-use matrix.

4.4.1.1. Fund elements used to assess the size of the constituent components.

Table 4.2 shows the available information about HA and LU of Andorra over a year (the reference year in this chapter is 2015). From a metabolic perspective, Andorra is an autopoietic system (Maturana and Varela, 1980) that self-organises by establishing a structural coupling with its context, i.e. by adapting its internal processes and structures to interact and respond to external factors such as economic, social and environmental conditions. Thus, maintaining Andorra's identity depends on biophysical elements inside and outside its political borders. Data about HA shows that the visiting population (tourists and one-day visitors) represent around 25% of the total, taking into account a "population equivalent" of 101 964 people calculated using the information from the Andorran Government (2016a).

Temporary workers represent an essential part of the workers for the Andorran economy, reaching percentages of more than 50% of the hours worked per year in critical sectors, such as the hotel sector, especially during the winter season (CRES, 2018). Around 92% of the total hours of human activity in Andorra are devoted to non-paid activities categorised as households and other users, and just 8% are dedicated to paid work activities. This percentage of human time in paid work is slightly lower compared with the 12% of Barcelona (Pérez-Sánchez et al., 2019) and the 10% in Catalonia (D'Alisa and Cattaneo, 2013).

As explained in Chapter 3, according to the theoretical concept of the dynamic energy budget, there must be a balance between the energy and materials required to express the various societal functions and the supplied flows generated by the primary and secondary sectors. The low proportion of time in the PW in Andorra indicates that this metabolic system is highly dependent on imports and the externalisation of productive processes. This characteristic is corroborated when verifying the distribution of working time between the economic sectors. The SG accounts for 87% of the working hours. This sum is above the value of 81% for Barcelona (Pérez-Sánchez et al., 2019) and well above that of Catalonia, which is 65% (Giampietro et al., 2012). This analysis flags the critical importance of tourism in the economy. The metabolic system of Andorra is typical of a tourism-driven system.

Table 4.2. Characterisation of the constituent components of Andorra at different levels of analysis.

Constituent components	*Human activity HA (Mh[a])*	*Land use LU (ha[b])*
N Andorra	**893**	**46 770**
N-1		
Households (HH)	600	472
Paid work (PW)	75	6 465
Other users[c]/NML[d]	218	39 833
N-2 (PW)		
Agriculture (AG)	1	2 058
Industry (ICM)	9	337
Services (SG)	65	4 070

[a]Mh: Millions of hours; [b]ha: hectares; [c]Other users: tourists not staying in private residences and one-day visitors (described only in hours); [d]NML: Non-Managed Land (described only in hectares). Sources: Own elaboration from CRES (2018), Andorran Government (2016a), CENMA-IEA (2012b), and Department of Statistics (2019a, 2019b).

Table 4.2 also displays information about land use. Andorra is a mountainous country with a total area of 46 770 ha of steep terrain. This explains that 85% of the territory is considered non-managed land. According to the land cover map (CENMA-IEA, 2012a), only 1.71% of the territory corresponds to urbanised areas. Based on estimated percentages from data on surface authorised for construction (Department of Statistics, 2019b), from the total land area of Andorra, 1% is devoted to urban and residential areas and, therefore, is associated with HH activities. Economic activities in the PW use 14% of the land, much of which goes to the SG (63%), followed by the AG (32%) and, with a residual character, the ICM (5%).

4.4.1.2. Economic variables.

Table 4.3 presents economic data relative to paid work activities in Andorra. In absolute terms, the SG accounts for the higher share of the GVA of Andorra, 88%, dominated by tourism and financial activities, followed by the ICM (11%). The AG, which is basically focused on tobacco growing and livestock activities, represents only 1% of the total. However, this analysis of the negligible role of agriculture does not consider other functions, such as preserving traditional landscapes and identities (e.g. home gardens). When looking at the intensive variable ELP, we can see a similar trend. The SG generates the highest monetary flow per hour worked, closely followed by the ICM (where sensitive activities with high value-added are included, such as generating and distributing electricity), with agriculture being the last. Regarding land use, the ELUP indicator shows that the industrial sector produces more than 118 times EUR per hectare than the agricultural sector and 150% more than services. As we will see, these high factors of production's productivity (labour and land) stem from a significant reliance on fossil fuels and, consequently, a dependence on external resources. This issue indicates that Andorra is an open metabolic system, where economic activities are primarily influenced by resources beyond the country's physical boundaries rather than the availability of resources within.

Table 4.3. Gross Value Added for the different economic activities in Andorra, as well as economic productivity per unit of hour of labour (ELP) and per unit of area devoted to each sector (ELUP).

Constituent components	*Gross value added GVA (M€[a])*	*Economic labour productivity ELP (€/h)*	*Economic land use productivity ELUP (€/ha)*
N Andorra	**2 242**	**2.5**	**47 937**
N-1			
Households (HH)			
Paid work (PW)	2 242	30	346 787
N-2 (PW)			
Agriculture (AG)	13	20	6 273
Industry (ICM)	251	27	744 595
Services (SG)	1 978	31	486 007

[a]M€: EUR Millions. Source: Own elaboration from CRES (2018), Andorran Government (2016a), CENMA-IEA (2012b), and Department of Statistics (2019a, 2019b, 2019c).

4.4.1.3. Energy.

4.4.1.3.1. Profile of energy types: extensive variables.

Table 4.4 presents the values of total energy throughput used in Andorra at different levels of analysis. Note that for the domestic sector, it has been possible to break down the requirements of various household functions. The transformation of the different energy carriers (i.e., electricity, heat, and fuel) into the corresponding gross energy requirement has been done by applying the "partial substitution method" —for details, see Giampietro et al. (2013).

The analysis of the total energy throughput at the level of the whole country (N) considering equivalent thermals units for the three energy types —electricity (E), fuels for heating (H) and fuels for transport (F)— shows a predominant use of E (52%), followed by F (26%) and, finally H (22%). It should be noted that the difference between the measurement of electricity in kWh and the measurement in thermal energy depends on the loss associated with the conversion of Joules of primary energy sources (consumed by power plants) into Joules of electricity.

At a lower level of analysis (N-1), the total requirements (GER) are distributed relatively evenly between the HH (45%) and the PW (55%). The analysis of the different energy types for the HH and the PW reflects the dominance of F in the HH, which accounts for 51% of the total energy use in this functional compartment. At the same time, the PW is dominated by E (expressed in thermal equivalent), 67% of the total. We can find a reason for the high consumption of F in the HH sector in the massive use of private vehicles both in internal (within the borders) and external (outside the borders) movements due to the low implementation of public transport and the lack of alternative options such as train. The automobile fleet is responsible for an average of 862 000 kilometres per day in Andorra (Miquel et al., 2014). At level n-2, the breakdown for the HH allows for determining the sub-functional compartments that require higher energy consumption: private mobility, heating and household electrical appliances. As expected, the highest consumptions in the productive sectors correspond to the SG with a preponderance of electricity consumption needed for running strategy structural elements such as hotels, department stores and ski resorts.

4.4.1.3.2. Metabolic relations: intensive variables.

Metabolic ratios make it possible to identify the energy requirements per hour of human activity (EMR) or per hectare (EMD), which, given the available technology and a determined set of social practices, are required to guarantee the functionality of the different societal compartments and the reproduction of the whole system (Table 4.5).

Table 4.4. Energy throughput in Andorra.

Constituent components	*Electricity E (GWh[a])*	*Electricity T.E.[b] E T.E. (TJ[c])*	*Heat H (TJ)*	*Fuel F (TJ)*	*GER[d] (TJ)*
N Andorra	**552**	**5 181**	**2 139**	**2 572**	**11 083**
N-1					
Households (HH)	140	1 314	709	2 090	4 979
Paid work (PW)	412	3 867	1 430	482	6 104
N-2 (HH)					
Air Conditioning	0	0			0
Sanitary hot water	12	113	110		234
Heating	22	210	599		869
Cooking	25	239			239
Household electrical	72	675			675
Lightning	8	77			77
Private mobility				2 090	2 885
N-2 (PW)					
Agriculture (AG)	n.a.	n.a.	n.a.	1	1
Industry (ICM)	12	112	38	38	207
Services (SG)	400	3 754	1 392	443	5 896

[a]GWh: Gijawatt hours; [b]T.E.: Thermal equivalent; [c]Terajoule; [d]GER: Gross energy requirement (Electricity T.E +1,1*Heat+1,38*Fuel). Source: Own elaboration from Travesset-Baro (2017) and Department of Statistics (2019a, 2019b, 2019d).

Table 4.5. Metabolic relations in Andorra.

	Exosomatic metabolic rate EMR					*Exosomatic metabolic density EMD*				
Constituent components	*Electricity E (kWh/h[a])*	*Electricity T.E. E T.E. (MJ/h[b])*	*Heat H (MJ/h)*	*Fuel F (MJ/h)*	*GER[c] (MJ/h)*	*Electricity E (MWh/ha[d])*	*Electricity T.E. E T.E.(GJ/ha[e])*	*Heat H (GJ/ha)*	*Fuel F (GJ/ha)*	*GER (GJ/ha)*
N Andorra	**0.6**	**5.8**	**2.4**	**2.9**	**12.4**	**11.8**	**110.8**	**45.7**	**55.0**	**237.0**
N-1										
Households (HH)	0.2	2.2	1.2	3.5	8.3	296.4	2 784.8	1 502.9	4 430.1	10 551.6
Paid work (PW)	5.5	51.7	19.1	6.4	81.6	63.7	598.1	221.1	74.5	944.2
N-2 (PW)										
Agriculture (AG)	n.a	n.a	n.a	1.2	1.7	n.a	n.a	n.a	0.4	0.5
Industry (ICM)	1.3	12.1	4.1	4.1	22.2	35.4	333.1	113.1	113.1	613.6
Services (SG)	6.2	57.9	21.5	6.8	91.0	98.2	922.4	341.9	108.8	1 448.7

[a]kWh/h: Kilowatt hour per hour; [b]MJ/h: Megajoule per hour; [c]Gross energy requirement; [d]MWh/ha: Megawatt hour per hectare; [e]GJ/ha: Gigajoule per hectare. EMR and EMD's maximum values are in blue and orange. Source: Own elaboration from Travesset-Baro (2017) and Department of Statistics (2019a, 2019b, 2019d).

In Andorra, the most elevated value of the EMR corresponds to the SG (91 MJ/h). The lower intensity in the use of energy per hour of work in the ICM indicates a minimal use of machinery, which can be attributed to the fact that Andorra's industrial sector consists of highly labour-intensive activities, such as the production of jams and cheeses as well as plumbing and construction companies. Given its traditional and marginal character, the AG does not have data available at the statistical level. Hence, a bottom-up approach is necessary to characterise the sector from the analysis of its structural elements (i.e. farms and processes of crop production at the field level). The notably lower EMR in the industrial sector compared to the service sector is an anomaly compared to other metabolic studies using MuSIASEM (Velasco-Fernández, 2017). This discrepancy highlights the absence of heavy industry industries. Concerning the level N-1, the HH is around ten times less energy-intensive than the PW. This issue is understandable if we consider the high percentage of hours of human activity devoted to the HH associated with sleeping and personal care, with low energy consumption.

The comparison of the EMD profiles for each functional compartment stresses the high energy use per hectare in the HH. This result is related to Andorra's high population density for the scale of the Pyrenees (163 inhabitants/km^2). Moreover, considering only the urbanised surface, the density reaches 10 000 inhabitants/km^2 (Miquel et al., 2014). It is important to note here that we are measuring land cover in which the residential area inside the apartments is a multiple of the external area occupied by the building. Such high densities can only be achieved by importing resources from outside (based on a stock-flow model), feeding the consumption of high-density buildings. It would be impossible to achieve these densities if the flows of food, energy carriers, and consumable products were generated using only the resources available in Andorra. Thus, the values of EMD help characterise Andorra as an open metabolic system whose metabolic rates are determined partially by the activities carried out within the system and partially by the externalisation of its economic activities and metabolic requirements.

4.4.1.4. Water.

Table 4.6 displays information on water consumption and metabolic relations using data from the Andorran Government (2016b). Water is classified into consumptive and non-consumptive uses. The former includes extracting water and returning it to the environment in a different place with the loss of quality and quantity (e.g., domestic, recreational, and agricultural uses). The latter includes the abstraction of water without modifying its quantity and quality.

Table 4.6. Water uses in Andorra.

Constituent components	*Water throughput WT (Mm^3)*[a]	*Consumptive use (Mm^3)*	*Non-consumptive use (Mm^3)*	*Water metabolic rate WMR (m^3/h)*[b]	*Water metabolic density WMD (m^3/ha)*[c]
N Andorra	**90.150**	**13.177**	**76.973**	**0.015**	**281.743**
N-1					
Households (HH)	5.547	5.547		0.009	11 755.951
Paid work (PW)	84.603	7.630	76.973	0.102	1 180.174
N-2 (PW)					
Agriculture (AG)	3.042	1.742	1.300	2.750	846.576
Industry (ICM)	74.502	0.021	74.480	0.002	63.679
Services (SG)	7.059	5.866	1.193	0.090	1 447.307

[a]Millions of cubic meters; [b]Cubic meters per hour; [c]Cubic meters per hectare. Source: Own elaboration from Andorran Government (2016b).

In the case of Andorra, the non-consumptive use of water primarily includes using water for electricity (ICM) and creating artificial snow (SG). Metabolic rates, i.e. WMR and WMD, are calculated only for consumptive uses. The distribution of the WT used in Andorra in consumptive uses at level N-1 shows that the economic activities (PW) account for 58% of the total. In comparison, residential activities (HH) account for 42% of the total. Within the economic activities, level N-2, the SG represents 77% of the PW concerning the consumptive use of water, followed by the AG (mainly by growing tobacco —23%). The ICM represents a marginal percentage of the water throughput for consumptive uses. However, it uses an essential fraction of non-consumptive uses (97%) to generate electrical energy.

Households are very intense in water use per hectare, around 11 756 m^3/ha. However, water consumption per unit of time is only 0.01 m^3/h in this sector. These numbers are due to household activities covering 67% of the total time in Andorra and occupying just a tiny fraction (1%) of the land cover. The distribution of the percentages of water withdrawal for urban (including household and services), agricultural, and industrial uses is diverse across countries, according to data from AQUASTAT (FAO, 2019). The profile for Spain, for instance, is 14% for urban, 67% for agriculture, and 19% for industry, with agriculture having the primary use. In comparison, the profile of Germany is 78%, 2%, and 20%, respectively, clearly dominated by urban uses. In

Andorra, the amount of water used for urban purposes (i.e. the consumptive use of water in the HH and SG) is 87% of the total consumptive use. Therefore, the pressure on water funds for urban uses is high, influenced by seasonality, temporary residents, and tourist activities (Reynaud et al., 2018). Moreover, considering only residents and urban uses, Andorra has an elevated water consumption, reaching a figure of 382 litres/day/resident (Andorran Government, 2016b), much higher than the European average of 128 litres/day/person (Aquae, 2020). It should be noted that this value is probably not due to high levels of final consumption but rather to high losses in the supply network (Andorran Government, 2016b).

4.4.2. Environmental pressures: GHG emissions and wastes.

Table 4.7 illustrates the environmental pressures connected to Andorra's metabolic pattern. GHG emissions for the different societal compartments and solid waste generation for level N have been considered. The emissions calculation was carried out using Travesset-Baro (2017) numbers. In this sense, the origin of the imported electricity and its corresponding emissions factors have been calculated using flat rates (Spain: 302gCO_2/kWh; France: 44gCO_2/kWh). Notably, for the reference year (2015), only 17% of the electricity consumed in Andorra was generated domestically, primarily through hydroelectric power, waste combustion, and a residual amount from photovoltaic solar energy. Finally, emissions from agricultural and livestock wastes have been included in the label "Other" (Miquel et al., 2021). Regarding the waste throughput, data for the different functional sub-compartments were unavailable. Still, it has been possible to segregate the different waste destinations (Andorran Government, 2016a).

Level N shows that the main energy carrier generating emissions is F (43%), followed by H (36%), both of which come entirely from imports. At the lower levels, N-1 and N-2 present the HH as the higher net contributor to GHG emissions (52%), followed by the SG (45%). A deeper analysis of the HH reveals that the energy carrier associated with more emissions is F (67%) due to the massive use of private vehicles. For its part, the SG generates the highest emissions due to using diesel for heating. It is essential to highlight that emissions from foreign transport companies performing services in Andorra are not included in the SG. Considering their inclusion, emissions from the energy carrier "F" would be significantly higher. Regarding waste generation, a relevant part (29%) is used as an input for the energy sector (in the ICM). The rest is exported for treatment or elimination generating environmental pressures on other SES.

Table 4.7. EPM for GHG emissions and solid waste.

	GHG Emissions					Solid Waste					
Constituent components	*Electricity E (tCO_2 eq)*[a]	*Heat H (tCO_2 eq)*	*Fuel F (tCO_2 eq)*	*Other (tCO_2 eq)*	*Total (tCO_2 eq)*	*Elimination (t)*[b]	*Energy recovery (t)*	*Recycling (t)*	*Other valuation (t)*	*Preparing for reuse (t)*	*Total (t)*
N Andorra	**89 444**	**159 432**	**190 688**	**5 860**	**445 424**	**2 280**	**34 087**	**26 221**	**50 390**	**1 026**	**114 004**
N-1											
Households (HH)	22 687	52 861	154 974		230 522						
Paid work (PW)	66 757	106 571	34 714		214 903						
N-2 (PW)											
Agriculture (AG)	n.a	n.a	58	5 860	5 918						
Industry (ICM)	1 938	2 843	2 825		7 606						
Services (SG)	64 819	103 728	32 831		201 378						

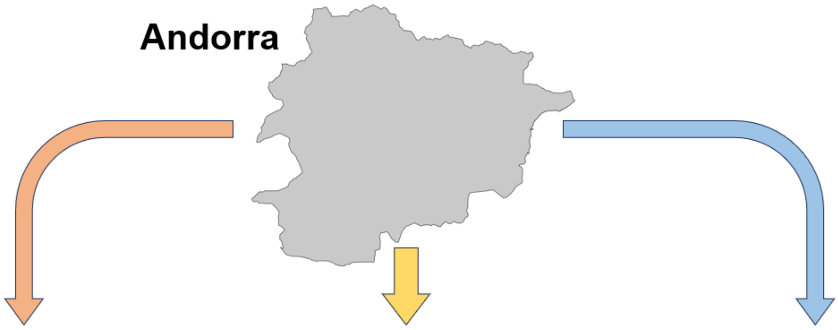
[a]tCO_2eq: tonnes CO_2 equivalent; [b]t: tonnes. Source: This is based on data from Travesset-Baro (2017), Department of Statistics (2019d) and Andorran Government (2016a).

4.4.3. The metabolic performance of Andorra: characterisation at level N.

Figure 4.6 synthesises the metabolic performance of Andorra for the average society. This metabolic analysis complements and contrasts traditional economic narratives by providing additional insights into the reliance on natural resources to perform economic activities, which is often overlooked in conventional approaches. Figure 4.6 compares the resource requirements (energy, water, land), GHG emissions, waste and value added: (i) to generate one Euro of value added (monetary performance); (ii) for each square meter of total land (land use performance); and (iii) for an hour of human activity considering the equivalent population of Andorra, i.e. including the activity of residents, tourists, one-day visitors and temporary workers (human activity performance).

4.5. Comparison with neighbouring countries.

The expression of a specific metabolic pattern is both impredicative and context-dependent. Social-economic systems express different metabolic patterns depending on their internal organisation and relationship with boundary conditions. Therefore, comparing Andorra's metabolic analysis findings with values from other countries or regions is essential for better contextualising the results. This section's analysis was based on information from different EU countries (for 2012), which appeared in Velasco-Fernández (2017). For the sake of comparability of data, it is considered that in the case of Andorra, HA of tourists and visitors included in the consignment "Other users" belong to the HH.



Monetary performance		
Land	0.2	m^2/€
Energy	4.9	MJ/€
Water	5.9	l/€
Emissions	0.2	Kg CO_2eq/€
Waste	0.1	Kg/€

Land use performance		
Value added	4.8	€/m^2
Energy	23.7	MJ/m^2
Water	28.2	l/m^2
Emissions	1.0	Kg CO_2eq/m^2
Waste	0.2	Kg/m^2

Human activity performance		
Value added	2.5	€/h
Energy	12.4	MJ/h
Water	14.8	l/h
Emissions	0.5	Kg CO_2eq/h
Waste	0.1	Kg/h

Figure 4.6. Metabolic performance of Andorra at level N. Source: Own elaboration.

4.5.1. Fund element HA.

Figure 4.7 shows the hours per capita (p.c.) assigned to the PW and HH in Spain, France, the EU and Andorra. The fraction of human activity invested in the PW indicates the structural pressure on the productive population. Thus, the given supply of paid work has to sustain the material standard of living of the whole population. Andorra allocates around 8% of human activity to paid work (733 hours p.c. of the 8 760 hours p.c. per year available). This percentage is slightly higher than that of Spain (7%) and the EU (6%) for the year 2012 and is very similar to the average percentage for the years 2000-2016 of the EU, which is around 8.5% (Velasco-Fernández et al., 2020b). The low number of hours per capita allocated to paid work in France represents an anomaly at the European level. Andorra is aligned with the European countries and can be considered a “mature” country, i.e. with high social protection, pensions for people with disabilities and a high percentage of dependent population, in contrast to other countries facing structural changes and with less dependent population, which usually allocate a higher percentage of human activity in the PW (e.g. China about 14.5%) (Velasco-Fernández et al., 2020b).

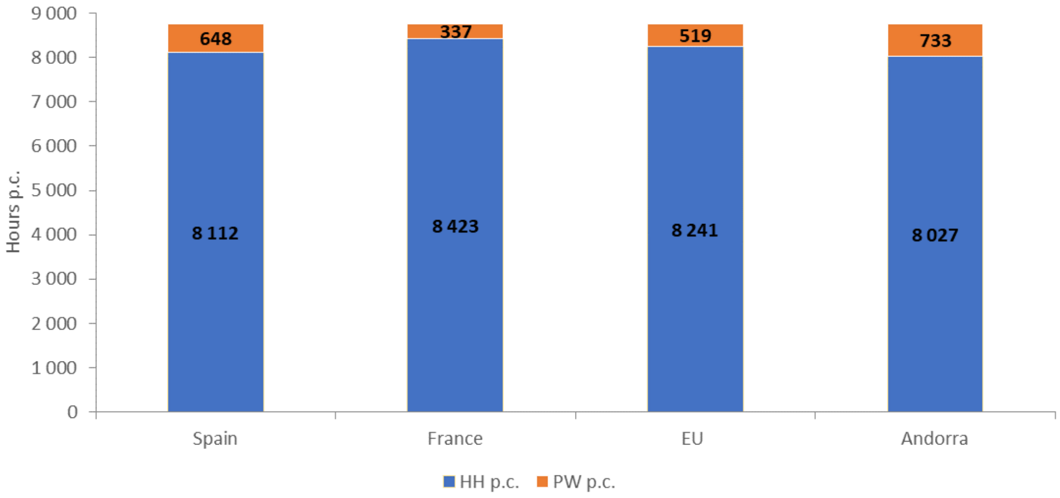


Figure 4.7. Hours per capita in Spain, France, the EU, and Andorra. Source: Own elaboration on data from Velasco-Fernández (2017) and CRES (2018).

Figure 4.8 shows Andorra's high specialisation in service and government activities regarding the allocation of hours p.c. within the different productive sectors.

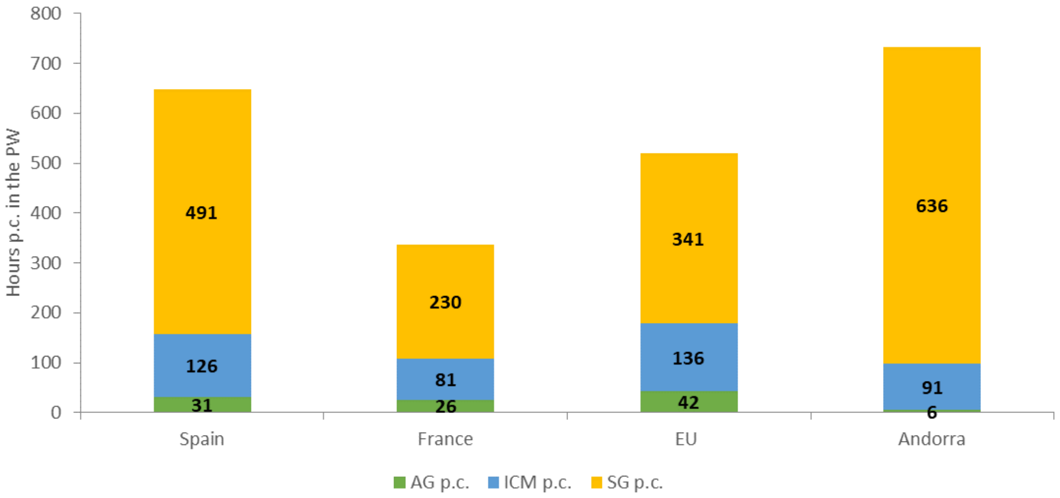


Figure 4.8. Hours per capita devoted to different productive sectors in Spain, France, the EU, and Andorra. Source: Own elaboration on data from Velasco-Fernández (2017) and CRES (2018).

Andorra dedicates only 6 hours p.c. of paid work to the AG compared to 31 in Spain and 42 in the EU. This suggests the externalisation of the production of the endosomatic energy requirements (i.e. food items) necessary for feeding its population. On the other hand, the high number of hours p.c. invested in the SG (636 compared to 491 in Spain or 341 in the average of the EU) also shows another external dependence:

that of tourists and one-day visitors who are necessary for the reproduction of the Andorran system.

4.5.2. Metabolic characteristics in relation to productivity and dissipation.

Figure 4.9 links the economic labour productivity (ELP) and the exosomatic metabolic rate (EMR), expressed in gross energy requirement (GER), of the countries considered at level N. At this level, society's characteristics are affected by extensive variables (size of the population and total resource consumption) and intensive variables (overall consumption per capita). The diameter of the circles represents the energy throughput per capita in GJ p.c. Figure 4.9 shows that higher levels of mechanisation correlate with increased economic productivity. Andorra exhibits an apparently decoupled energy-productivity performance because of its minimal industrial sector.

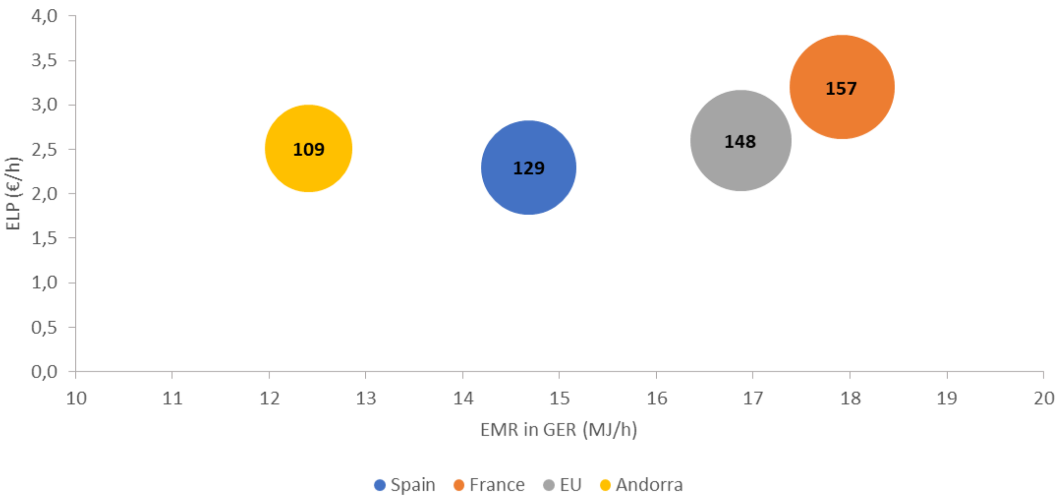


Figure 4.9. Exosomatic metabolic rate (EMR) and economic labour productivity (ELP) at level N for Spain, France, EU, and Andorra. The diameter of the circle represents the energy throughput per capita in GJ. Source: Own elaboration on data from Velasco-Fernández (2017), CRES (2018) and Department of Statistics (2019a, 2019c, 2019d).

Andorra achieves a labour productivity (2.5 €/h) similar to that of the EU (2.6 €/h), above that of Spain (2.3 €/h) and lower than that of France (3.2 €/h). Furthermore, Andorra's energy requirements per hour of human activity (12 MJ/h) and per capita (109 GJ) are lower than those of the surrounding countries considered (for instance, 15 MJ/h in Spain and 17 MJ/h in the EU and 129 GJ p.c. in Spain and 148 GJ p.c. in EU). These metabolic characteristics seem logical given the inexistence of an industrial sector demanding high energy requirements — between 200 and 1 400 MJ/h in the case of high energy intense sectors and between 50-200 MJ/h in the case of medium energy intensity sectors (Giampietro et al., 2012, p.270).

Considering a different level of observation, at level N-1, it is possible to compare the exosomatic metabolic rate (EMR) in the PW and HH with again the diameters of the circles representing the energy throughput p.c. (Figure 4.10). The EMR in the PW can be considered a proxy of the technical capitalisation of the industry (i.e. mechanisation and computerisation, making the activities more competitive in the market or more effective in public services). In contrast, this intensive variable in the HH is a proxy of the material standard of living (i.e. power capacity introduced to facilitate household chores, higher comfort and private mobility). Therefore, high EMR values indicate an elevated society's mechanisation and modernisation level related to its energetic (and resource) dependency on its environment (Velasco-Fernández et al., 2020a).

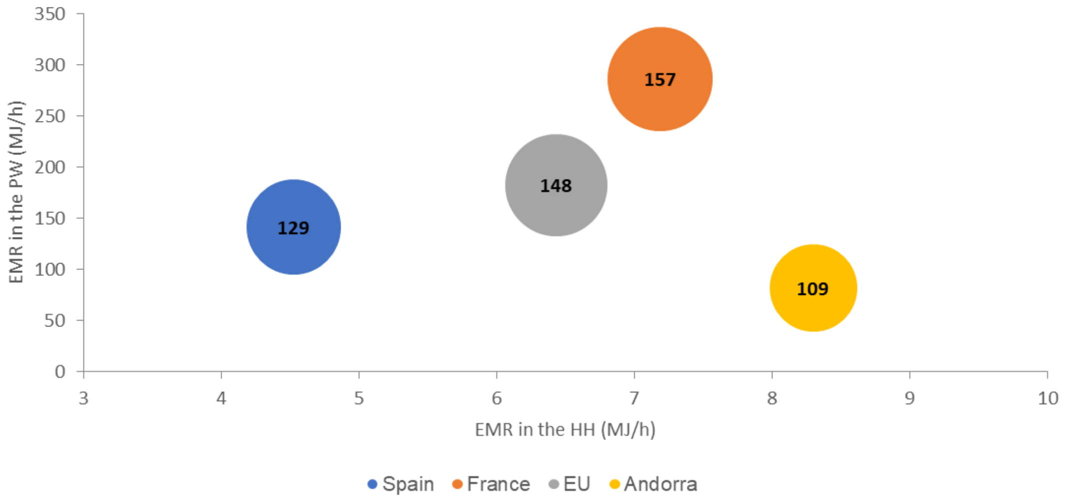


Figure 4.10. Exosomatic metabolic rate (EMR) in the paid work sector (PW) and household sector (HH) for Spain, France, the EU, and Andorra. The diameter of the circle represents the energy throughput per capita in GJ. Source: Own elaboration on data from Velasco-Fernández (2017), CRES (2018) and Department of Statistics (2019a, 2019d).

The PW in Andorra has an EMR which represents 45% of that of the EU (around 82 MJ/h versus 183 MJ/h). On the other hand, Andorra has an exceptionally high value of the EMR in the HH sector (8.3 MJ/h) that contrasts with the 6.4 MJ/h of the EU, the 4.5 MJ/h of Spain and surpasses the 7.2 MJ/h of France. In this sense, the value of Andorra is closer to countries like Canada (8.8 MJ/h) and the USA (10 MJ/h) (values for 2008) (Chinbuah, 2010) or European countries like Finland (9.8 MJ/h) or Sweden (8.3 MJ/h) (values for 2016) (Velasco-Fernández et al., 2020b). As the EMR in the HH serves as a proxy for the technification of homes and private mobility, it is likely associated with dwellings with numerous appliances, climate systems, and a high rate of private vehicles per family. Beyond this higher material standard of living and comfort, this value could also be linked to urban sprawl, larger houses, and the climate conditions of Andorra. The high EMR value in the HH observed in Andorra contrasts with those in lower-income countries such as China (2 MJ/h), Venezuela (2.1 MJ/h), Brazil (1.4 MJ/h) for the year 2000 (Eisenmenger et al., 2007) or Bulgaria (1.4 MJ/h), Romania (1.8 MJ/h), Poland (2.4 MJ/h) and Hungary (3.1 MJ/h) in 2004 (Iorgulescu and Polimeni, 2009). The high per capita income in Andorra compared to the EU —reflected in a GDP per capita of €35 014 (Department of Statistics, 2019c) versus €31 020 in the EU in 2015 (Velasco-Fernández, 2017)— seems to correlate with the higher use of energy per hour in the HH found in Andorra. Additionally, other forms of wealth generation, particularly those linked to financial operations and capital gains, that are not directly tied to biophysical value-added production processes should be considered when analysing Andorra's material standard of living. This issue is especially relevant given Andorra's unique status as a non-EU country with a favourable tax differential compared to neighbouring countries and its classification as a tax haven until 2018 (El País, 2018). Thus, Naredo's (2019) reflection on how the ideology of CE —viewing the economic process as a self-sustaining merry-go-round between production and consumption— obscures other ways of generating financial wealth that do not fit within the production and sale of goods and services seems particularly relevant in this case.

Finally, Figure 4.11 relates the economic labour productivity (ELP) and the corresponding exosomatic metabolic rate (EMR) in the SG for the countries considered (this time, the area of the figures is not associated with any observable attribute). The levels of Andorra's monetary flow generated per hour of work in the SG and the energy requirements (in GER) per hour of work in the SG are similar to those of Spain: 31 €/h and 91 MJ/h in Andorra versus 30 €/h and 99 MJ/h in Spain. In contrast, the economic and metabolic performance of Andorra in the SG appears to diverge significantly far from the values of the EU and France.

The results discussed for Andorra in this section, primarily based on Velasco-Fernández (2017), appear to be supported by the benchmarks established in Giampietro et al. (2012) where: (i) the ELP for the European countries is set between 2-4 €/h (p.48), with Andorra's value at 2.5 €/h; (ii) the EMR (in GER) for the average society is considered to be between 20-30 MJ/h (p.48), with Andorra slightly below at 12 MJ/h; (iii) the EMR in the HH is established between 2-8 MJ/h (p.264), with Andorra at 8.3 MJ/h; and (iv) the EMR in the SG is found to be between 30-100 MJ/h (p.264), with Andorra at 91 MJ/h.

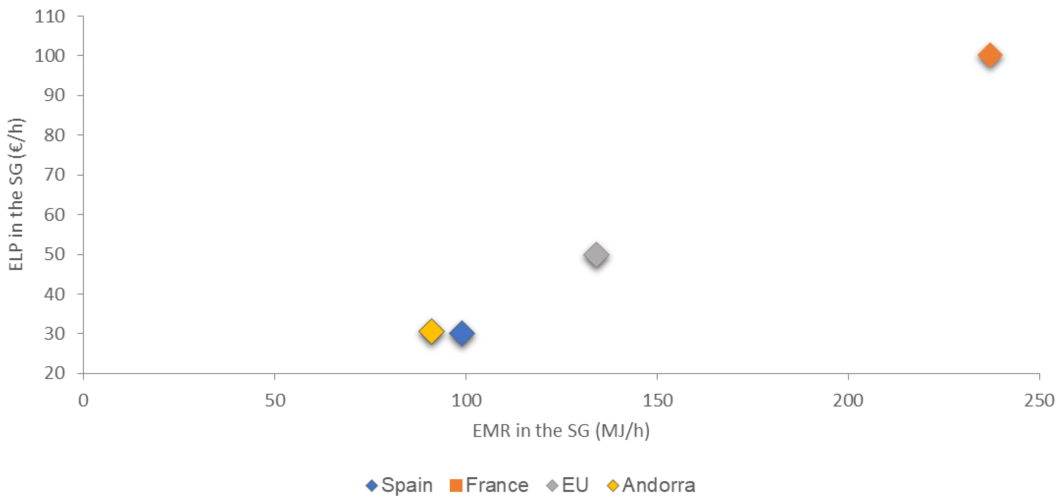


Figure 4.11. Exosomatic metabolic rate (EMR) and economic labour productivity (ELP) in the service and government sector (SG) for Spain, France, the EU, and Andorra. Source: Own elaboration on data from Velasco-Fernández (2017), CRES (2018) and Department of Statistics (2019a, 2019c, 2019d).

4.6. Comparing the societal metabolism of two tourism-intensive regions: Menorca and Andorra.

In this section, the metabolic profile obtained for Andorra is compared with the metabolic characterisation of Menorca based on the work of Marcos-Valls et al. (2020), with both using 2015 as a reference year.

4.6.1. The fund elements HA and LU.

Andorra and Menorca can be considered good examples of open metabolic systems. Many human activities and environmental goods and services necessary for maintaining their identities come from outside their borders. In Menorca, 16% of its total human activity comprises temporary residents (Marcos-Valls et al., 2020), whereas in Andorra, this figure rises to 24%. Figure 4.12 breaks down the hours per capita dedicated to each functional compartment where “Other users”, i.e. tourists not staying in private residences and one-day visitors, are included in the HH.

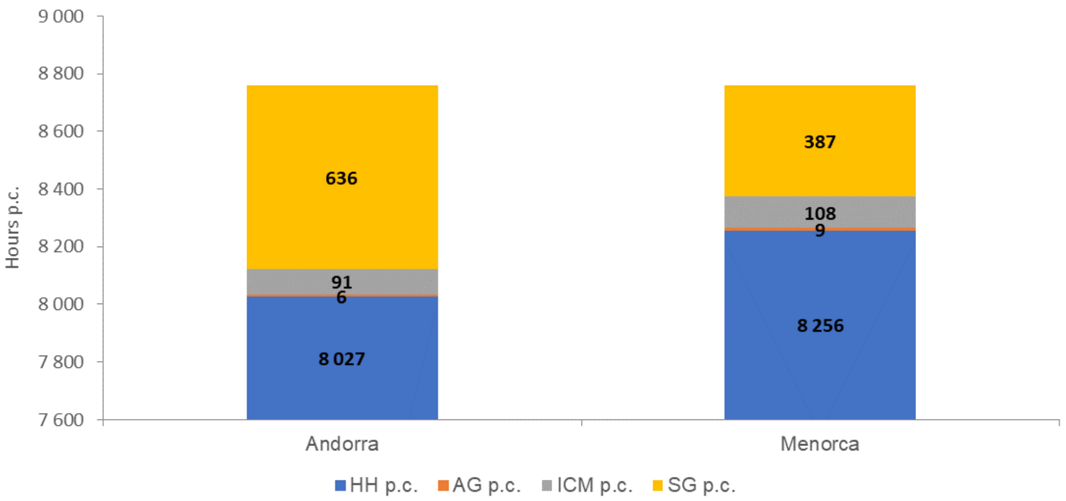


Figure 4.12. Hours per capita per year devoted to the functional compartments considered in Andorra and Menorca. Source: Own elaboration on data from Marcos-Valls et al. (2020) and CRES (2018).

Andorra exhibits a higher percentage of human activity devoted to the PW (8%) compared to Menorca (6%). While both economies are affected by the seasonality of tourism and a transient population, the lower social coverage in Andorra —such as the absence of unemployment insurance— may contribute to this difference. Additionally, Figure 4.12 illustrates Andorra's significant specialisation in the SG, with 633 hours p.c. out of the 8 760 hours available, compared to 387 hours p.c. in Menorca. Conversely, Andorra's agricultural sector remains relatively minor, contributing only to 6 hours p.c. compared to 9 hours p.c. in Menorca.

Figure 4.13, for its part, displays the distribution of the fund element LU in m^2/p.c. dedicated to each functional compartment. A notable feature of Andorra is the high percentage of non-managed land (85% versus 54% in Menorca). This is mainly due to its mountainous terrain, which concentrates the residential and productive land uses in the centres of ancient glacial valleys. In addition, modernisation processes in Andorra have involved converting agricultural land use to urban land (CENMA-IEA, 2012b). In contrast, Menorca's designation as a Biosphere Reserve[17] has fostered sustainable strategies to protect the environment (UNESCO, 2018). In Andorra, the SG, which includes ski resorts, has the highest proportion of LU p.c. among productive sectors.

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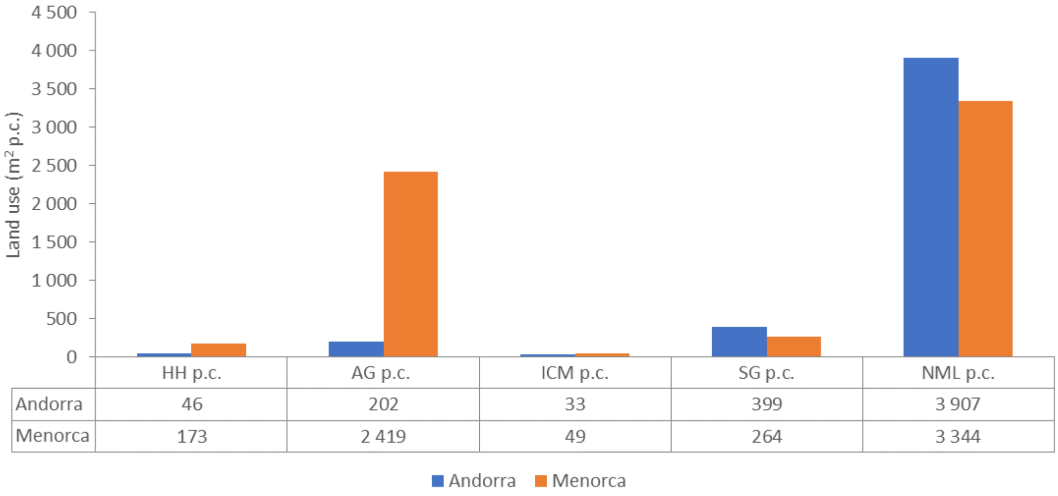
[17] Ordino, one of the seven parishes of Andorra, achieved the distinction of a Biosphere Reserve in 2020. https://biosferaordino.ad/

Meanwhile, in Menorca, the AG features the most extensive land use per capita at 2 419 m^2 p.c. between paid work sectors.



	HH p.c.	AG p.c.	ICM p.c.	SG p.c.	NML p.c.
Andorra	46	202	33	399	3 907
Menorca	173	2 419	49	264	3 344

Figure 4.13. Land use per capita in Andorra and Menorca. Source: Own elaboration on data from Marcos-Valls et al. (2020) and CENMA-IEA (2012b).

4.6.2. Economic variables.

Figure 4.14 illustrates the relationships between economic variables: economic labour productivity (ELP, in €/h), economic land use productivity (ELUP, in €/ha), and the gross value added per capita (€ p.c.) —represented by the bubble size— considering the equivalent population. Andorra demonstrates, compared to Menorca, a higher productivity per hour of HA at 2.5 €/h versus 1.6 €/h, and per hectare of land at 47 937 €/ha versus 22 880 €/ha, respectively. In addition, the generation of added value per capita in Andorra is 65% higher than in Menorca (21 988 € p.c. in Andorra and 14 300 € p.c. in Menorca). These values correlate with the higher percentage of hours dedicated to the PW in Andorra. Despite having a population equivalent of 92% of Menorca's, Andorra's GVA is 141% higher than the island's.

4.6.3. Energy throughput.

Regarding energy throughput, Andorra uses different energy carriers than Menorca. Figure 4.15 represents the requirements per capita of the different energy carriers, i.e. Electricity (E) in thermal equivalent (T.E), heat (H), and fuel (F), for the two SES considered. Both systems have E as the primary energy carrier, followed by F and H in the last place. Andorra shows higher per capita consumption of E and H compared to

Menorca, with values 137% and 860% greater, respectively. In contrast, Andorra exhibits lower per capita use of F, with consumption representing 74% of Menorca.

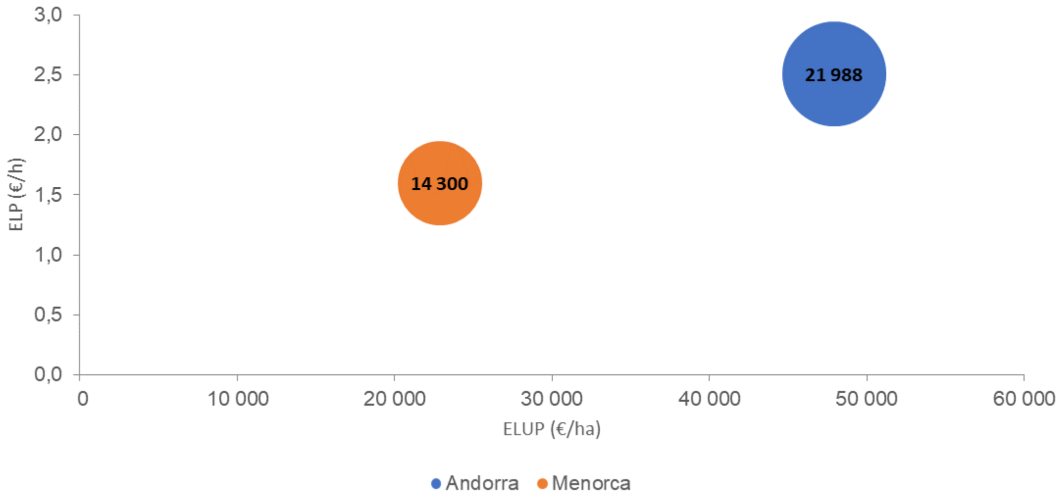


Figure 4.14. Economic labour productivity (ELP) and economic land use productivity (ELUP) in Andorra and Menorca. The circle's diameter represents the gross value added per capita (€ per capita). Source: Own elaboration on data from Marcos-Valls et al. (2020), CENMA-IEA (2012a), CRES (2018) and Department of Statistics (2019c).

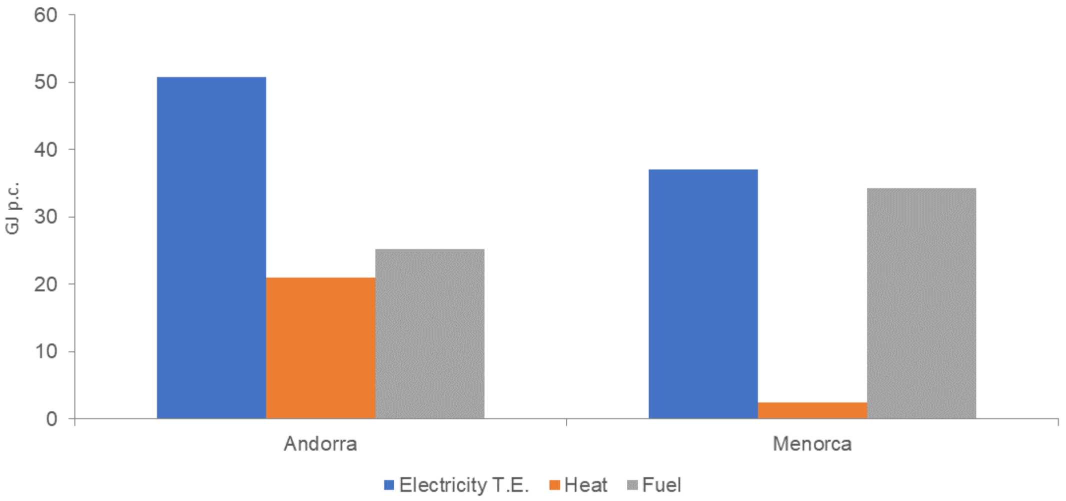
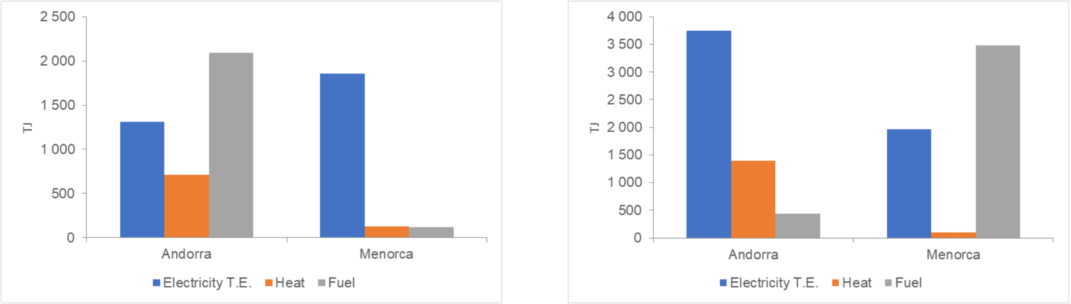


Figure 4.15. Energy throughput in Andorra and Menorca expressed in Gigajoules per capita in 2015. Source: Own elaboration from Marcos-Valls et al. (2020) and Department of Statistics (2019a, 2019d).

Descending in the observation level and comparing the two most relevant functional compartments in Andorra with the respective ones in Menorca —the HH and the SG— it is possible to observe a different pattern of energy carrier consumption (see Figure 4.16).



(a - HH) (b - SG)

Figure 4.16. Energy carriers' consumption —electricity in thermal equivalent, heat, and fuel— in TJ for the household sector (HH) (a), and the service and government sector (SG) (b), in Andorra and Menorca. Source: Own elaboration from Marcos-Valls et al. (2020) and Department of Statistics (2019a, 2019d).

The bottom-up analysis made for the HH in Andorra (Table 4.4) reveals that heating and sanitary water account for significant energy consumption in the domestic sphere, comprising 53% of the total, excluding private transport. These domestic functions are primarily met with domestic diesel, which explains the high value of the energy carrier H in Andorra. No similar analysis is available for Menorca. However, the substantial use of E in the HH on the island is likely because heating, sanitary water and air conditioning (necessitated by the island's mild climate) are primarily powered by E. The difference in F consumption in the HH between the two systems is mainly due to the widespread use of private transport in Andorra. The principality only offers coach services for foreign destinations (and counting with a small airport outside its geographic boundaries). In contrast, the high F consumption in Menorca's SG is due to the inclusion of transportation to the mainland in the service sector, such as airline companies and naval vessels. In the absence of a more detailed analysis of the subsectors that make up the SG in both systems, the more significant requirement of E in Andorra (almost double than in Menorca) seems to be linked to the characteristics of its main structural elements, such as large retail centres, financial companies, ski areas, and more.

4.6.4. Metabolic characteristics in relation to productivity and dissipation.

Figure 4.17 combines the exosomatic metabolic rate values (MJ/h) in the PW and HH for the considered areas. The bubble diameter indicates GER's energy throughput per capita (measured in GJ p.c.).

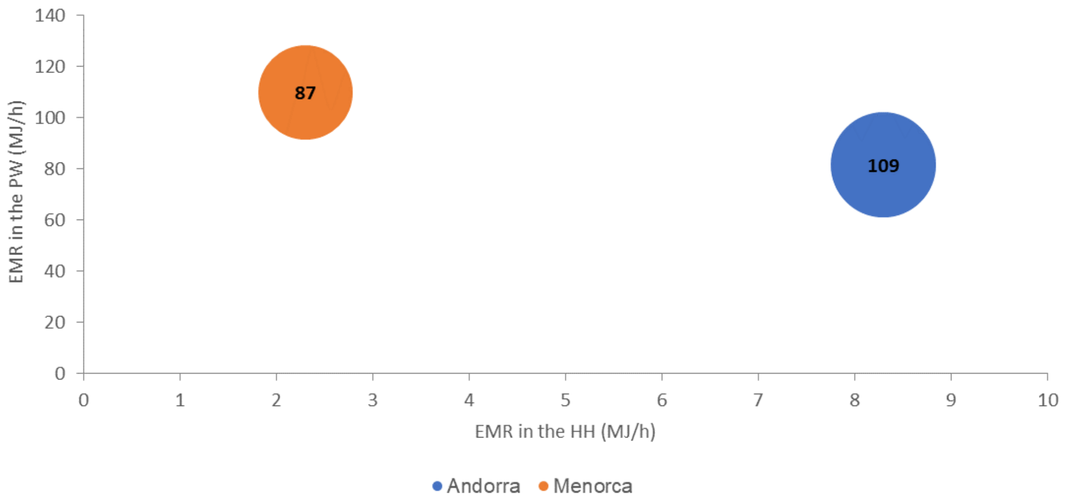


Figure 4.17. Exosomatic metabolic rate (EMR) in the household sector (HH) and paid work sector (PW) in Andorra and Menorca. The diameter of the circle represents the energy throughput per capita in GJ. Source: Own elaboration from Marcos-Valls et al. (2020) and Department of Statistics (2019a, 2019d).

A complexity-based approach necessitates connecting different levels and dimensions, as the values obtained vary depending on the level of analysis. Andorra has more significant exosomatic energy requirements per capita than Menorca (109 GJ p.c. versus 87 GJ p.c.). However, when we looked at the PW, Menorca reached higher values of the EMR (110 MJ/h —Menorca— 82 MJ/h —Andorra). Although total energy throughput requirements in the PW are pretty similar, with each using around 6 100 TJ of GER, the difference lies in the lower number of hours worked in the productive sectors in Menorca (75% compared to Andorra's total) and the presence of highly energy-intensive industries on the island, particularly in the transport sector. Do not forget that the EMR is defined as the quantity of exosomatic energy transformed per hour of human activity. The use of power capacity drives this indicator. In that sense, we use it as a proxy of the level of capitalisation of the sectors: how much technical capital (machinery, devices and infrastructure in a broad sense) is used to perform a particular activity. Data corroborate the findings from the previous section on exosomatic energy use per hour of HA in the residential sector. Specifically, Andorra's value is nearly four times higher than Menorca's, with figures of 8.3 MJ/h compared to 2.3 MJ/h.

Finally, Figure 4.18 illustrates the relationship between the economic labour productivity (ELP, in €/h), the exosomatic metabolic rate (EMR, in MJ/h of GER) and the energy throughput (in TJ of GER) for the SG (level N-2) in Andorra and Menorca. The size of the bubbles represents the proportional weight of resource use, with larger bubbles indicating higher extensive values.

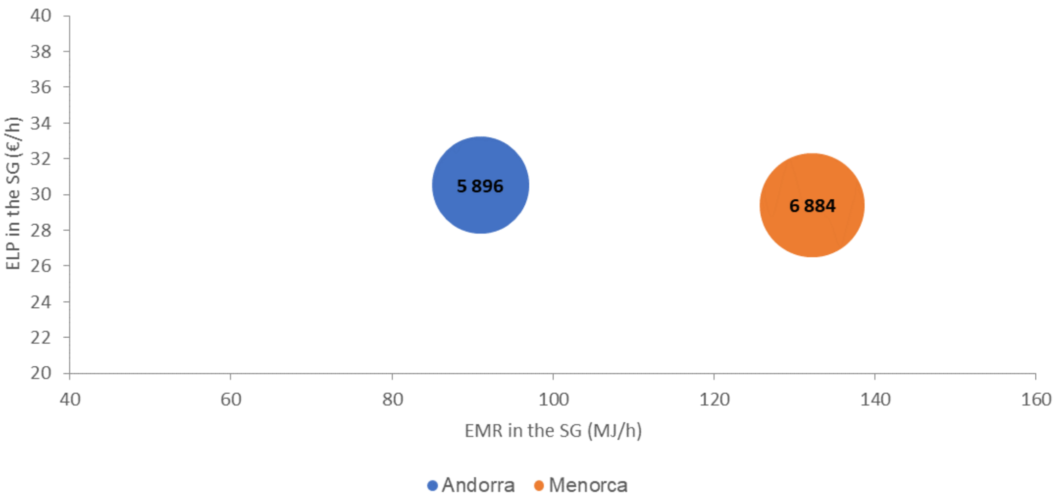


Figure 4.18. Exosomatic metabolic rate (EMR) and economic labour productivity (ELP) for the service and government sector (SG) in Andorra and Menorca. The circle's diameter represents the total energy consumption in the SG in TJ. Source: Own elaboration from Marcos-Valls et al. (2020) and Department of Statistics (2019a, 2019c, 2019d).

The generation of value added per hour worked in the SG in the principality is slightly higher than that of the island (31 €/h versus 29 €/h). On the other hand, as a whole, the SG in Andorra presents a value of the EMR 31% lower than that of Menorca (91 MJ/h versus 132 MJ/h). Moreover, the total energy requirements in the SG are 14% lower in Andorra compared to those of Menorca (5 896 TJ versus 6 884 TJ). For a more accurate analysis, a detailed breakdown of the requirements and metabolic patterns of the various subsectors within the SG would be necessary, but obtaining such disaggregated data is currently not feasible.

4.6.5. Water throughput and water metabolic rates.

Figure 4.19 compares water requirements (only consumptive use in mega cubic meters) of the different societal compartments in Andorra and Menorca. The requirements for the HH are similar in both areas. So are the requirements for the SG, which in the case of Menorca exceed those of Andorra by 5%. However, the main difference is in the AG, where Menorca has much greater needs (more than six times Andorra's requirements). In this sense, Menorca has an important milk and cheese production system, and traditional farming plays a crucial role in shaping and maintaining landscape and traditional identity (Marcos-Valls et al., 2020). On the other hand, the modernisation process developed in Andorra in the second half of the 20th century has seen the importance of the AG (under natural endowments that are already difficult for agricultural practice) gradually diminish towards commercial and tourist activities. Considering total water consumption, Menorca's value is 90% higher than Andorra's.

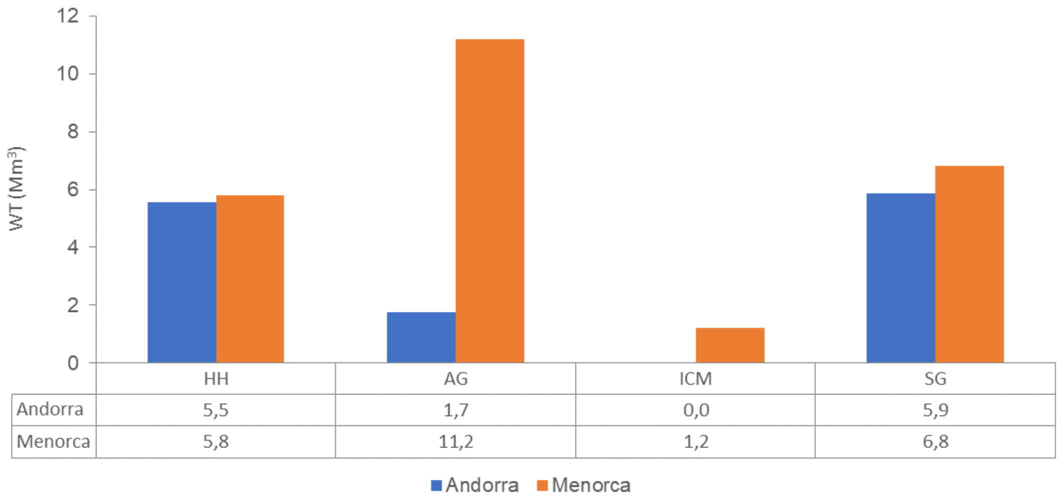


Figure 4.19. Water throughput (WT) in consumptive uses for the different societal compartments in Andorra and Menorca. Source: Own elaboration on data from Marcos-Valls et al. (2020) and Andorran Government (2016b).

Figure 4.20 shows the HH and SG's water metabolic rate (WMR, in cubic meters per hour) in Andorra and Menorca. The size of the bubbles represents per capita water consumption (consumptive uses) in cubic meters, normalised by the equivalent population to allow comparison between systems with great openness.

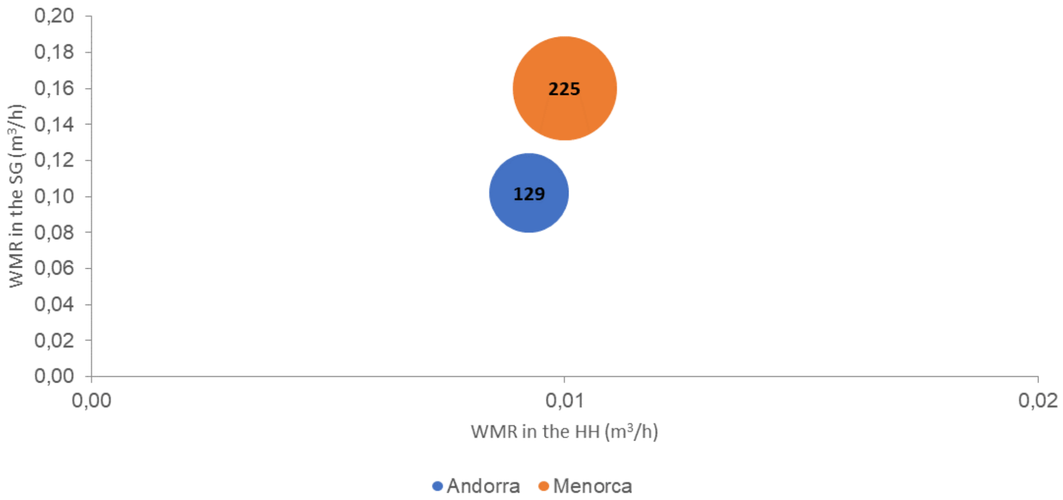
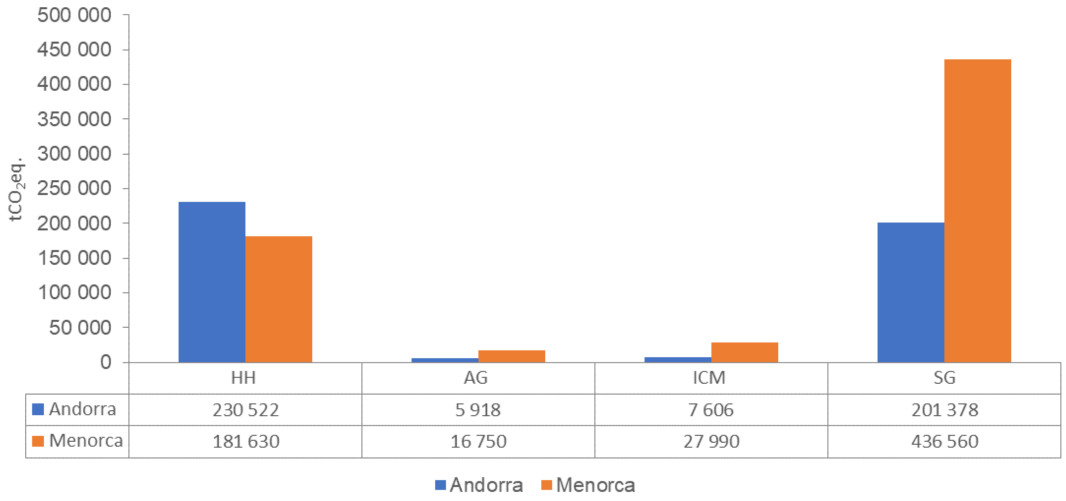


Figure 4.20. Water metabolic rate (WMR) in the household sector (HH) and the service and government sector (SG) in Andorra and Menorca. Source: Own elaboration on data from Marcos-Valls et al. (2020), Andorran Government (2016b) and Department of Statistics (2019a).

We observe how both systems have the same water consumption ratio per hour in the HH (around 0.01 m^3/h). Moreover, values in the PW are ten times higher (Andorra) and 16 times higher (Menorca) than household values, indicating that activities generating monetary value are more intense water users per hour than residential activities. As expected, considering the total water requirements, the consumption of water per capita value in Menorca is 74% higher than that in Andorra (225 cubic meters p.c. versus 129 cubic meters p.c.), given the more extensive water consumption in Menorca with a similar population concerning Andorra.

4.6.6. GHG emissions.

Figure 4.21 breaks down GHG emissions (in $tCO_2eq.$) quantities across various societal compartments. Total emissions of Andorra represent 67% of those of Menorca. This lower environmental pressure is partly due to Andorra's importation of electricity from France, which, owing to its reliance on nuclear power, has a lower emission factor than Spain. However, this benefit comes with other environmental challenges, such as managing radioactive waste. In both systems, the emissions calculated do not account for the energy requirements and emissions externalised through imports associated with the production and transportation of imported commodities goods, which are subsequently consumed within their respective borders.



	HH	AG	ICM	SG
■ Andorra	230 522	5 918	7 606	201 378
■ Menorca	181 630	16 750	27 990	436 560

Figure 4.21. GHG emissions in Andorra and Menorca. Source: Own elaboration on data from Marcos-Valls et al. (2020), Travesset-Baro (2017) and Department of Statistics (2019d).

The highest emissions in the residential sector in Andorra are probably due to the use of domestic fuel for heating and the massive use of private transport. On the other hand, the generalised use of electricity in the SG in Andorra and the consumption of fuel in the SG in Menorca (related to tourists' transport) could explain the higher emissions found in the SG in Menorca.

4.7. Conclusions.

Biophysical analyses are a necessary step before embarking on sustainable development plans. The MuSIASEM analysis provides a systematic and multidimensional perspective of the biophysical requirements for Andorra's constituent components to fulfil their functions. Achieving more sustainable state-pressure relations —such as reducing the quantity of resource use or altering metabolic rates— will inevitably affect Andorra's identity and operations. As highlighted by the literature on societal metabolism (Giampietro et al., 2012; González de Molina and Toledo, 2014), changing metabolic patterns is challenging, and large-scale socio-ecological transformations often involve the emergence of "Promethean" technologies such as agriculture or the use of fossil fuels (Arenas et al., 2022). Moreover, the integrated analysis flags the existence of biophysical constraints affecting decision-making option space. Social and political factors are only a part of the dimensions to be considered. Andorra's total available hours and initial land endowment limit its self-organisation potential. Along with these biophysical constraints, social and institutional factors —such as ordinary legal working hours and unemployment insurance— play crucial roles in determining the productive possibilities of the country.

The analysis also underscores the complex relationship between economic productivity and environmental pressure. Sustaining dissipative structures, such as people and different types of land uses, and achieving economic performance are intricately linked to metabolic flows. In the case of Andorra, each inhabitant requires 109 GJ of energy (in GER) per year and 129 m^3 of water for consumptive uses. Furthermore, each EUR of GVA is associated with using 5 MJ of energy, 6 litres of water, 0.2 $kgCO_2eq$. of GHG emissions and the generation of 0.1 kg of waste. Similarly, the production of residential space is tied to the use of 1 055 MJ/m^2 of energy (in gross energy requirement) and the consumption of 1 175 l/m^2 of water. Understanding the complex interplay between economic productivity and environmental pressure is crucial for sustainable development planning.

Andorra operates as an open system from a metabolic perspective, meaning that the resources within its physical boundaries do not solely dictate its economic activities. Given its strong focus on tourist and financial services, Andorra lacks a productive sector capable of supplying the goods and services needed to maintain its identity. The HH and SG (the two large functional compartments of Andorra) present a significant resource outsourcing, reducing the internal environmental pressures and externalising pressures on other SES. In the case of energy, only 17% of the electricity consumed in Andorra is produced domestically (hydroelectric generation, waste burning and a residual fraction from photovoltaic solar energy). Additionally, 100% of fuels for heating and transportation are imported. Total energy requirements (in GER) are distributed relatively evenly between the HH (45%) and the PW (55%). The analysis of the different energy types for the HH and the PW reflects the dominance of F in the HH, which accounts for 51% of the total energy use in this functional compartment. At the same time, the PW is dominated by E (measured in thermal equivalent), 67% of the total. Regarding intensive values, the EMR's most elevated value corresponds to the SG (91 MJ/h), whereas the EMD has its maximum in the HH 10 552 (GJ/ha).

The analysis of water gives a different picture. The water uses of the various societal compartments considered come from Andorra resources. The distribution of the WT used in Andorra in consumptive uses shows that the economic activities (PW) account for 58% of the total. In comparison, residential activities (HH) account for 42% of the total. Within the economic activities, the SG represents 77% of the PW concerning the consumptive use of water, followed by the AG (mainly by growing tobacco — 23%). The ICM represents a marginal percentage of the water throughput for consumptive uses. However, it uses an essential fraction of non-consumptive uses (97%) to generate electrical energy. Households are very intense in water use per hectare, around 11 756 m^3/ha, whereas water consumption per unit of time is only 0.01 m^3/h in this sector. However, a different picture can be obtained if the water requirements for producing the food items and energy carriers consumed in Andorra are considered. Thus, concerns about nexus security and environmental burden shifting should be taken more seriously.

Andorra is not only dependent on biophysical flows produced elsewhere. The country also depends on the fund element HA from outside its borders (in the form of tourists and temporary workers) to maintain its identity. Therefore, a shortage of human time in one or more critical functions of the social-economic system can constrain the trajectory of economic growth in the same way that other biophysical production factors, such as water, energy, and land, do. In this way, the country is vulnerable to external events, such as the COVID crisis, that can reduce the number of tourists and one-day visitors, highlighting its vulnerability given its extreme specialisation in tourism and service activities and its insertion in the global flows of people.

Andorra's productivity per hour of labour (ELP) aligns with that of its neighbouring countries. However, due to the lack of an energy-intensive industrial sector, Andorra has lower per capita energy requirements (109 GJ in GER) and lower power capacity in the productive sector (82 MJ/h in GER) compared to its neighbouring countries and the average values for the EU. Despite this, the country demonstrates a high material standard of living in the residential sector, as evidenced by its high EMR (8.3 MJ/h). Moreover, Andorra's per capita energy use is higher than that of other tourist destinations such as Menorca (109 GJ p.c. in GER versus 87). However, energy use in the SG per hour of work (i.e. the EMR in the SG) is less intensive than in Menorca (82 MJ/h in GER versus 110), mainly due to its limited transport service infrastructure. Consequently, future projects to extend this infrastructure will have important implications for evaluating progress towards meeting international climate agreements and achieving a carbon-neutral economy.

Finally, it is crucial to recognise that assessing the metabolic performance and pressures in using energy, water, emissions and wastes, and the economic productivity of labour and land uses provides a comprehensive understanding of Andorra's operational dynamics. The approach reveals the broader context, linking socioeconomic activities with environmental limits at a systemic level where metabolic-repair systems operate. However, it is essential to note that the results presented so far are based on aggregated values at a coarse scale —covering the entire country and significant economic sectors. For these results to effectively inform policy, they should be integrated with more detailed analyses. Future research should include a breakdown of the metabolic performance and pressures across subsectors within the SG (e.g. the hotel industry or the ski areas) or various residential types in the HH using bottom-up information based on the analysis of technical coefficients tailored to specific research questions. This would involve using the analytical concept of metabolic processors. In any case, the initial characterisation presented so far has shown the possibility of the MuSIASEM framework to (i) integrate information that is often analysed independently and (ii) identify how the metabolic pressure and performance of different elements determining the metabolic pattern of the whole is relevant when discussing the sustainability of the system.

4.8. Chapter references.

Andorra Business, 2023. Advantages of investing in a business in Andorra [WWW Document]. https://www.andorrabusiness.com/en/invest/advantages-investing-business/ (accessed 10

August 2024)

Andorran Government, 2016a. Revisió del Pla Nacional de Residus d'Andorra (2017-2020). Goven, d'Andorra, Andorra la Vella.

Andorran Government, 2016b. Estudi per a l'elaboració anyal de l'inventari i quantificació de la despesa hídrica per usos del Principat d'Andorra-Any 2015. Govern d'Andorra, Andorra la Vella.

Aquae, F., 2020. Consumo de agua por persona y día en Europa [WWW Document]. URL https://www.fundacionaquae.org/europa-consumimos-una-media-128-litros-agua-persona-dia/ (accessed 22 December 2020)

Arenas, L., Naredo, J.M., Riechmann, J., 2022. Bioeconomía para el siglo XXI. Actualidad de Nicholas Georgescu-Roegen. Los Libros de la Catarata, Madrid.

BOPA, 2023. Edicte del 15-2-2023 pel qual es publica la guia tècnica per a la coordinació dels estudis de càrrega màxima parroquials. Butlletí Oficial del Principat d'Andorra, Andorra la Vella.

BOPA, 2018. Llei 21/2018, del 13 de setembre, d'impuls de la transició energètica i del canvi climàtic (Litecc). Butlletí Oficial del Principat d'Andorra, Andorra la Vella.

BOPA, 2009. Llei 35/2008, del 18 de desembre, del Codi de relacions laborals. Butlletí Oficial del Principat d'Andorra, Andorra la Vella.

Cañada, E., 2018. Un turismo sostenido por la precariedad laboral. Papeles Relac. Ecosociales y camnbio Glob. 140, 65–73.

CENMA-IEA, 2012ª. Mapes de cobertes del sol d'Andorra [WWW Document]. https://www.iea.ad/mapa-de-cobertes-del-sol-d-andorra-2012 (accessed 13 Desember 2020).

CENMA-IEA, 2012b. Memòria del mapa de cobertes del sòl d'Andorra (MCSA) de l'any 1972. Comparativa amb el MCSA de l'any 1995.Institut d'Estudis Andorrans, Sant Julià de Lòria.

Chinbuah, A., 2010. International comparison of the exosomatic energy metabolic profile of developed economies. MSc. Thesis.

CRES, 2018. Estudi sobre el mercat de treball d'Andorra. Centre Recerca Sociològica, Andorra la Vella.

D'Alisa, G., Cattaneo, C., 2013. Household work and energy consumption: a degrowth perspective. Catalonia's case study. J. Clean. Prod. 38, 71–79. https://doi.org/10.1016/j. jclepro.2011.11.058.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56. https://doi.org/10.1029/2017RG000591

Department of Statistics, 2019a. Demographic, social and economic statistics [WWW Document]. https://www.estadistica.ad/portal/apps/sites/#/estadistica-en (accessed 5 April 2020)

Department of Statistics, 2019b. Superfície autoritzada [WWW Document]. http://www.estadistica.ad (accessed 5 April 2020)

Department of Statistics, 2019c. Agregats macroeconòmics [WWW Document]. http://www.estadistica.ad (accessed 5 April 2020)

Department of Statistics, 2019d. Consum d’energia elèctrica i importacions de carburans [WWW Document]. http://www.estadistica.ad (accessed 5 April 2020)

Eisenmenger, N., Ramos-Martín, J., Schandl, H., 2007. Análisis del metabolismo energético y de materiales de Brasil , Chile y Venezuela. Rev. Iberoam. Econ. Ecológica 6, 17–39.

El País, 2018. Andorra sale de la lista de paraísos fiscales de la Unión Europea [WWW Document]. https://elpais.com/economia/2018/12/05/actualidad/1544035685_784039.html# (accessed 23 August 2024)

FAO, 2019. AQUASTAT. Water withdrawal by sector [WWW Document]. http://www.fao.org/nr/water/%0Aaquastat/data/query/results.html (accessed 29 March 2020)

Giampietro, M., 2019. On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. Ecol. Econ. 162, 143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001.

Giampietro, M., 2018. Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10, 1–17. https://doi.org/10.3390/su10072545

Giampietro, M., Mayumi, K., 2000a. Multiple-scale integrated assessment of societal metabolism: introducing the approach. Popul. Environ. 22, 109–153. https://doi.org/10.1023/A:1026691623300

Giampietro, M., Mayumi, K., 2000b. Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales. Popul. Environ. 22, 155–210. https://doi.org/10.1023/A:1026643707370

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London. https://doi.org/10.4324/9780203107997

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Societies : Where Economists Fall Short. Routledge, London.

Giampietro, M., Renner, A., 2020. The Generation of Meaning and preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria, in: Braha, D., et al. (Ed.), Unifying Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

González de Molina, M., Toledo, V.M., 2014. The Social Metabolism. A Socio-Ecological Theory of Historical Change. Springer International Publishing, Berlin. https://doi.org/10.4324/9781315679747-14

Harvey, D., 2019. La lógica geográfica del capitalismo. Icaria editorial, Barcelona.

Iglesias-Pérez, F., Blanco-González, A., Navalón, J.G.M., 2018. Informal economy and legitimacy. The Spanish case., in: Díez-De-Castro, E., Peris-Ortiz, M. (Eds.), Organizational Legitimacy. Springer, pp. 231–242.

Iorgulescu, R.I., Polimeni, J.M., 2009. A multi-scale integrated analysis of the energy use in Romania, Bulgaria, Poland and Hungary. Energy 34, 341–347. https://doi.org/10.1016/j.energy.2008.09.003

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge.

Komac, B., de la Parte, I., Riba, L., Pladevall, C., Fanlo, R., Roquet, M., 2020. Pastures comunes i ramaderia a Andorra. Usos, gestió i perspectives. Institut d’Estudis Andorrans, Andorra la Vella.

Lluelles, M.J., García, E., 2018. Història econòmica d’Andorra, segles XX-XXI. Universitat d’Andorra, Sant Julià de Lòria (Andorra).

Marcos-Valls, A., Kovacic, Z., Giampietro, M., Kallis, G., Rieradevall, J., 2020. Isolated yet open: A metabolic analysis of Menorca. Sci. Total Environ. 738, 139221. https://doi.org/10.1016/j.scitotenv.2020.139221

Maturana, H.R., Varela, F.J., 1980. Autopoiesis and Cognition: The Realization of the Living. D. Reidel Publishing, Dordrecht.

Melgar-Melgar, R.E., Hall, C.A.S., 2020. Why ecological economics needs to return to its roots: The biophysical foundation of socio-economic systems. Ecol. Econ. 169, 106567. https://doi.org/10.1016/j.ecolecon.2019.106567

Miquel, C., Armengol, J.L., Dobarro, J., Rovira, N., 2014. Premier Rapport Bisannuel de l’Andorre a la Convention Cadre des Nations Unies sur les Changements Climatiques. Govern d’Andorra, Andorra la Vella.

Miquel, C., Cuyàs, M., Boneta, A., 2021. Cuarto informe bianual de actualización de Andorra ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Govern d’Andorra, Andorra la Vella.

Naredo, J.M., 2019. Taxonomía del lucro. Siglo XXI, Madrid.

Nicolis, G., Prigogine, I., 1977. Self-Organization in Nonequilibrium Systems. Wiley, New York.

Nilsson, M., Griggs, D., Visbeck, M., 2016. Policy: Map the interactions between Sustainable Development Goals. Nature 534, 320–322. https://doi.org/10.1038/534320a

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., Ripa, M., 2019. Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. Energy Policy 124, 13–22. https://doi.org/10.1016/j.enpol.2018.09.028

Reynaud, A., Pons, M., Pesado, C., 2018. Household Water Demand in Andorra: Impact of Individual Metering and Seasonality. Water 10. https://doi.org/10.3390/w10030321

Travesset-Baro, O., 2017. Prospectiva energètica al Principat d’Andorra. Model integrat d’avaluació de la seguretat energètica per a la transició cap a un escenari sostenibilista. Universitat Politècnica de Catalunya (PhD Thesis).

UNDP, 2019. Human Development Index-Andorra [WWW Document]. https://hdr.undp.org/data-center/specific-country-data#/countries/AND (accessed 7 March 2020)

Velasco-Fernández, R., 2020. Depoliticizing and repolicizing SDGs., in: The MAGIC Consortium (Ed.), The Nexus Times. Megaloceros Press, Bergen. https://doi.org/10.24994/2020/nexustimes

Velasco-Fernández, R., 2017. The Pattern of Socio-Ecological Systems. A Focus on Energy, Human Activity, Value Added and Material Products. Universitat Autònoma de Barcelona (PhD Thesis).

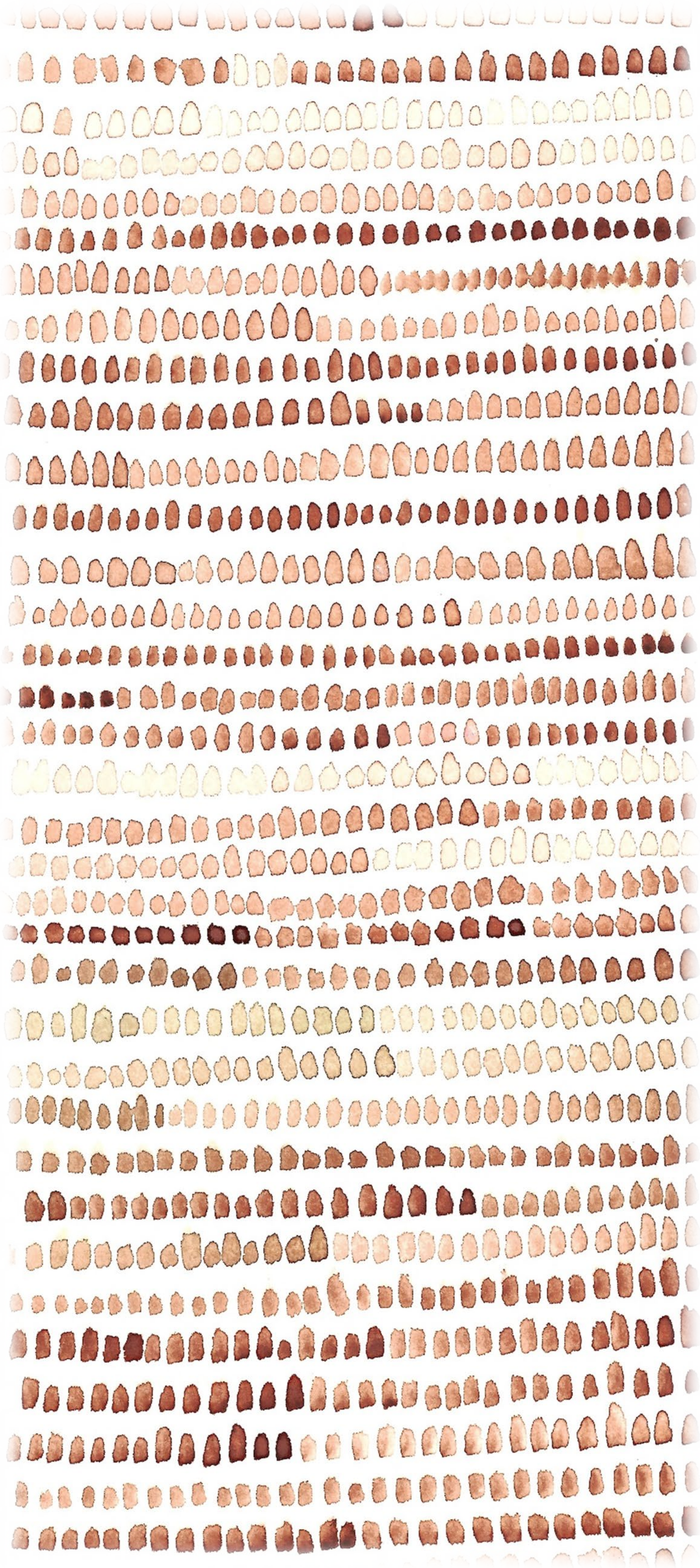
Velasco-Fernández, R., Dunlop, T., Giampietro, M., 2020ª. Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy. Energy Policy 137. https://doi.org/10.1016/j.enpol.2019.111089

Velasco-Fernández, R., Pérez-Sánchez, L., Chen, L., Giampietro, M., 2020b. A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. Energy Strateg. Rev. 32, 100562. https://doi.org/10.1016/j.esr.2020.100562

Williams, J., Bouzarovski, S., Swyngedouw, E., 2019. The urban resource nexus: On the politics of relationality, water–energy infrastructure and the fallacy of integration. Environ. Plan. C Polit. Sp. 37, 652–669. https://doi.org/10.1177/0263774X18803370

World Bank, 2019. GDP per capita (current US$)-Andorra [WWW Document]. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=AD&most_recent_value_desc=true (accessed 7 March 2020)

Chapter 5



5. Characterising Andorra's endosomatic and exosomatic metabolism dependence on externalised processes[♦].

> "Let's get out of this country".
> Camera Obscura[*].

5.1. Introduction.

The previous chapter underscored the profound dependence of Andorra's metabolic pattern on biophysical elements outside its political borders. This chapter delves into an externalisation analysis, a matter of pressing concern given the recent and urgent geopolitical issues that have brought energy and food security to the forefront of the political debate. The coronavirus pandemic and the Ukrainian war have starkly demonstrated the complexity and vulnerability of the world economy. During the pandemic, several world chains became disrupted for critical products such as medical products (Badreldin and Atallah, 2021) or microchips (Hopkins, 2021). The ongoing war in Ukraine and the resulting sabotage of the Nord Stream gas infrastructure have shed light on the implications of the EU's dependence on energy imports and fossil fuels (Tollefson, 2022). This situation has also exacerbated food insecurity (Ben Hassen and El Bilali, 2022). Consequently, annual inflation (2022-2023) of over 10% in energy and food goods (Eurostat, 2023) has driven oil and gas prices to their highest levels in nearly a decade and increased cost-of-living pressures.

The EU's energy policy has long been focused on decarbonising the economy and enhancing energy security (European Commission, 2019, 2015). Similarly, efforts have been made to promote more sustainable agrarian production models, exemplified by policies like the "Farm to Fork Strategy," which emphasises local production (European Commission, 2020). The recent surge in energy market prices and concerns about the stability of energy and food supply chains have intensified political pressure to expedite the transition towards less import-dependent energy and agricultural sectors. These geopolitical uncertainties have exposed sustainability gaps within the European states, necessitating a greater reliance on local resources and a heightened focus on

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[♦] This chapter is mainly based on Larrabeiti-Rodríguez et al. (n.d.).

[*] Title of the third studio record of the Scottish band *Camera Obscura,* released by Elephant Records in 2006.

security. As a result, there have been renewed efforts to reduce dependence on fossil energy sources (European Commission, 2022) and food imports (Caprile, 2022).

Predictably, Andorra's energy targets align with those of neighbouring EU countries. The Andorran energy system is more than 90% dependent on foreign sources, with 80% of electricity and 100% of fossil fuels imported (OECC, 2021). This and other factors, such as the continuous growth in energy demand, the risk of saturation of electricity import lines, the constant increase in fuel prices and electricity tariffs, and the desire to comply with European energy directives, motivated the Law on the Energy Transition and Climate Change Impetus ("Litecc" by its acronym in Catalan) (BOPA, 2018). With its ambitious goals, this legislation lays the foundations for more sustainable development by reducing energy dependence, boosting domestic production, and achieving carbon neutrality by 2050 through renewable energy sources. The government has also implemented an energy-saving plan in response to recent geopolitical incidents (Andorran Government, 2022). Meanwhile, the existing agriculture and livestock law (BOPA, 2000) supports agricultural activity, acknowledging its vital role in limiting urban expansion, preserving the natural environment and landscape, and enhancing local food consumption.

An informed debate on security should address sustainability, sovereignty, and resilience (Kovacic and Di Felice, 2019). This task also requires a biophysical consumption-based perspective considering trade (Roca-Jusmet and Padilla-Rosa, 2021). The dynamics of globalisation result in a disconnect between consumers, producers, and the environment that supports them. Likewise, trade acts as a mechanism displacing socio-environmental pressures such as land use change, labour, GHG emissions, or the depletion of water resources toward export-producing nations. A consumption-based accounting reveals the implications of externalisation processes by quantifying the socio-environmental pressures and impacts embedded in imports (Ripa et al., 2021). This approach also enables us to comprehend the neo-colonial dependence of importing countries on different territories (Hickel et al., 2022) while evaluating a particular region's lack of sovereignty and self-sufficiency. Finally, it poses ethical concerns about the various responsibilities of individual countries in maintaining their citizens' lifestyles through massive externalisation of production factors, which leads to habitat destruction and the transfer of environmental pressures to other regions (Peng et al., 2016). This concern calls for an analysis related to the concept of environmental footprint (Matuštík and Kočí, 2021). For these reasons, using a consumption-based perspective is crucial to reveal the limitations of sustainability policies (Krähmer, 2020). However, current consumption-based assessments have predominantly focused on narrow perspectives, such as the ecological footprint (Rees and Wackernagel, 1996), particularly within a “carbon-centred worldview” (Moreno et al., 2015), while often neglecting other critical environmental issues and the socioeconomic dimension of sustainability (Fang et al., 2013).

Recognising the limitations of single indicators, metabolic perspectives offer a richer multidimensional approach (Giampietro et al., 2012; Haberl et al., 2021), closely aligned with nexus heuristics in integrated analyses of interconnected phenomena, such as the water-food-energy nexus (Brouwer, 2022; Giampietro et al., 2020). Like living organisms, societal systems are metabolic systems with a metabolism characterised by expected patterns of energy and material flows for their functioning and structural reproduction (Sorman, 2015). Societal metabolism comprises two distinct categories: endosomatic and exosomatic processes (Georgescu-Roegen, 1971; Lotka, 1925). Endosomatic metabolism refers to the physiological conversion of different energy inputs (i.e. food items consumed) within the human body into end uses, such as applied human muscle power, enabling societal reproduction. On the other hand, exosomatic metabolism refers to the energy converted outside the human body to enhance useful work output through activities like using tractors, melting metals, or air transportation (i.e. energy carriers used). The stability of society’s endosomatic metabolism is linked to food security, while the stability of exosomatic metabolism is tied to energy security (Giampietro et al., 2014).

This chapter studies both types of metabolism by exploring the biophysical dependence of Andorra’s exosomatic and endosomatic metabolism from other territories. Drawing from MuSIASEM, the chapter reflects on the different constraints faced by the energy and food systems of Andorra, aggravated by the growing perception of biophysical insecurity. The method enables the integrated assessment of local metabolic performance and the externalisation effects in energy and food systems. Ripa et al. (2021, p. 2) define externalisation as “the set of entangled social, economic and environmental effects stemming from the displacement of extractive and productive industries outside of governance boundaries”. In other words, externalisation refers to the indirect use of resources and the resulting socioenvironmental impacts outside a reference system through imports. Two key conceptual elements are maintained throughout the analysis: (i) the coupling between structural and functional elements following Koestler's notion of holons (Koestler, 1967); and the distinction between fund and flow elements following Georgescu-Roegen's flow-fund model (Couix, 2020).

The rest of the chapter is structured as follows: Section 5.2 reviews current consumption-based perspectives. Section 5.3 stresses some theoretical aspects mentioned previously, which are crucial to contextualise the results presented in this chapter (5.3.1) and outlines the rationale to characterise processes of the food and energy systems to account for externalisation (5.3.2). Section 5.4 defines the boundaries considered for the case study of Andorra. Results and discussions are presented in section 5.5, covering the diagnosis of Andorra's endosomatic and exosomatic metabolism (5.5.1) and the externalisation of energy (5.5.2) and food (5.5.3). The assessment's limitations are discussed in 5.5.4. The chapter closes with conclusions in section 5.6.

5.2. Literature review on consumption-based approaches.

Generally, a territorial "production-based approach" uses conventional resource efficiency indicators. These indicators propose policies to decouple natural resource use and environmental impacts from economic growth. In this narrative, the goal of "dematerialisation" is achieved by using less material, energy, water and land resources to generate the same economic output (UNEP, 2011). For instance, official GHG emission inventories use a territorial approach for commitments, negotiations and declarations of intent under the UNFCCC (Roca-Jusmet and Padilla-Rosa, 2021). Also, the idea of green growth currently refers to such visions (OECD, 2011). However, these indicators are based on assessments of direct resource use, which cannot fully describe the overall biophysical requirements associated with the production and use of imports. Moreover, since countries in a highly globalised world are increasingly involved in international trade, the largest importers of materials and resources (i.e. high-income industrial countries) can meet their emissions and other resource targets by externalising energy and material-intensive processes to other countries. This strategy may seriously undermine the effectiveness of global policies (Jiborn et al., 2018).

A consumption-oriented perspective takes trade into account. Estimating resources embodied in trade is basically done via three approaches: The first approach uses environmentally extended multi-regional Input-Output (MRIO) models (Wiedmann et al., 2007) to trace inter-industry deliveries through the economy and between economies down to final demand categories. The second approach uses coefficients from the LCA of products (European Union Joint Research Center, 2010), with which traded goods are multiplied to calculate the upstream material, energy and water or land requirements. In addition, these approaches can be combined in so-called “hybrid” approaches such as the Environmentally Extended Economic Input-Output Life Cycle Assessment (Weber et al., 2009) among others (Bjørn et al., 2020), which present critical epistemic challenges (Guinée et al., 2022). A third approach is the footprint family (Galli et al., 2012), composed of ecological, carbon, and water footprints and differs from LCA (Vanham et al., 2019).

These approaches, as with any other method, have particularities and limitations. Input-output models adopt a macroscale approach. The reference system is the national economy in a specific year, and in resource terms, they focus on the amount of (and kind of) material extracted domestically in that year. With the help of coefficients, these materials are allocated to final demand categories within the country and to exports. On the global level, no comprehensive input-output table exists for the global economy. National input-output tables must be interlinked to MRIO models. This is a very complex procedure and requires several assumptions that still need to be fully standardised, although progress has been made in this regard (Tukker et al., 2018).

For the LCA approach, the system’s reference is the extraction-production-consumption chain of specific products or groups of products. The basic idea is to assess all environmental burdens connected to a product or service consumed in a particular country in a specific year, irrespective of where and when they were produced. Since the early 1990s, significant efforts have been made to create LCA inventories for a wide variety of products and services and to standardise procedures (Frischknecht et al., 2007). The original purpose of LCA was to guide comparison between products and services across a standardised set of indicators for environmental burden, among them resource use. However, the findings of LCA analyses are valid only within the narrow context defined by its epistemic rationale, which seeks to compare the environmental performance of supply systems, ignoring the relevance of systemic societal aspects, such as the quantity of labour available, determining the overall characteristics of the SES in which theses supply systems are embedded. Moreover, LCA results are susceptible to the system’s boundaries definition and allocation criteria: choosing different boundaries or allocation criteria leads to significantly different assessments for the same product or service (Heijungs and Suh, 2002; Wang et al., 2011).

Finally, footprint accounting, initially proposed in the 1990s as Ecological Footprint by Rees (1992), has evolved to assess many other environmental issues and gained widespread acceptance among sustainability indicators. Despite that, the concept has not reached the same level of unification and standardisation as the LCA. Moreover, a large variety of methodological approaches are often hidden under the same name, leading to incomparability of assessments and overall confusion (Matuštík and Kočí, 2021).

None of these approaches used to assess externalisation includes a clear distinction between primary flows (inputs and wastes) and secondary inputs (requiring the consideration of embodied primary energy sources or embodied energy carriers, such as embodied coal, oil or nuclear electricity, as in Ripa et al. (2021)). Nor is it clear the distinction between flow elements, i.e. those which do not maintain their identity throughout an analysis (e.g. food and electricity are examples of flow elements) and fund elements, i.e. those which maintain their identity during analysis (e.g. a person, over a year, retains his identity, assuming it consumes a proper flow of food and exosomatic inputs). Therefore, this chapter proposes a methodology based on MuSIASEM that can bridge different pieces of information together (from the microscale of technical conversions to the macroscale of the whole country) to understand the system under analysis better and provide a more comprehensive view of countries' metabolism including their dependence on other territories. To do this, a transparent framework of assumptions across scales, across types of resources (primary flows vs secondary inputs) and nexus elements (water as a flow element and land as a fund element) is required. Of course, the use of the methodology is not hermetic. It allows complementarity with other approaches presented here, as in Martin et al. (2023), where LCA functionality is connected with the relational capabilities of MuSIASEM to asses energy issues.

5.3. Methodology.

5.3.1. MuSIASEM and the epistemic tool of the metabolic processor.

As explained in Chapter 3, according to MuSIASEM's perspective, social-economic systems rely on the environment to survive. To maintain their identity, they must constantly obtain resources from the environment and dispose of resulting wastes back into it. The consideration of this forced relationship implies modifying our level of observation. Our sustainability analysis should focus on a SES (Berkes et al., 2003; Holling, 2001) determined by the activities expressed by a given set of ecosystems —in the ecosphere (Rees, 1999)— and a given set of social actors and institutions —in the anthroposphere[18] (Kuhn and Heckelei, 2010). It is important to remember here that the methodology suggests considering different sustainability concerns related to distinct biophysical constraints concerning: (i) an external view of feasibility focused on the appropriation of primary flows —such as oil, water or minerals (which need primary supply provided by nature)— and the generation of primary wastes and emissions —such as plastic waste or GHG (which need sink capacities provided by nature— in the ecosphere, associated to a quantitative assessment with the EPM; and (ii) an internal view of viability, focused on the use of secondary inputs (e.g energy carriers and food) and required funds under human control (e.g. hours of human labour or hectares of land use) in the anthroposphere, translated into a quantitative assessment with the EUM.

In turn, MuSIASEM uses the metabolic processor as a tool to represent the different elements of a complex system, i.e. the different "holons" in the jargon of hierarchy theory (Ahl and Allen, 1996), which are described by a set of expected relations over metabolic processors (see section 3.3.3). A metabolic processor expresses a metabolic pattern described as a profile of inputs generating a profile of outputs at a given hierarchical level. This tool can be imagined as analogous to the enzyme concept describing cells' metabolism or an extended production function in biophysical economic analysis. They are data arrays used to represent patterns combining data that belong to non-equivalent descriptive domains (e.g. an hour of work, cubic metres of water, hectares of land use and kWh of electricity). The idea of the processor, initially introduced in relational analysis by Robert Rosen, helps to identify the relationship between functional and structural elements, arising from the definition of a shared final cause (i.e. the generation of a useful function that is defined based on the context where a determined element belongs to) (Louie, 2010).

Metabolic processors are used to characterise the structural and functional elements of a complex system. Structural elements are tangible elements such as a hydroelectric power plant or a meat sheep farm. These structural elements are

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[18] The terminology of "technosphere" and "biosphere", common in the methodology and used in Chapters 3 and 4, has been replaced by the terms "ecosphere" and "anthroposphere" to underline the fact that the anthroposphere includes not only technical but also symbolic and institutional issues. In turn, human beings are part of life and, therefore, belong to the "biosphere" but depend on the processes happening in the ecosystems, which are by far more than their biological part (e.g. a gold mine). Hence, the term "ecosphere" is used. This amendment came after a conversation with my colleague Ansel Renner, who developed this and other ideas in his thesis (Renner, 2020).

associated with structural typologies sharing a standard set of metabolic attributes, i.e. inputs and outputs profiles (e.g. expected values associated with the biophysical performance of a hydroelectric power plant or a meat sheep farm). Different structural typologies can be combined to express a functional type, i.e. a notional representation of expected profiles of inputs and outputs (e.g. expected values associated with the biophysical performance of the electric sector or meat production sectors). When implementing relational analysis, different components of a complex system (e.g. the various structural and functional elements of an energy or food system) can be represented by metabolic processors. Metabolic processors are defined as oval, characterising unitary processors (used to represent structural elements) describing normalised relations (i.e. expressed in a unitary description) over the profile of inputs and outputs. Conversely, metabolic processors are represented as rectangular (used to define functional elements) when providing extensive values describing observed processes in their actual size (Figure 5.1).

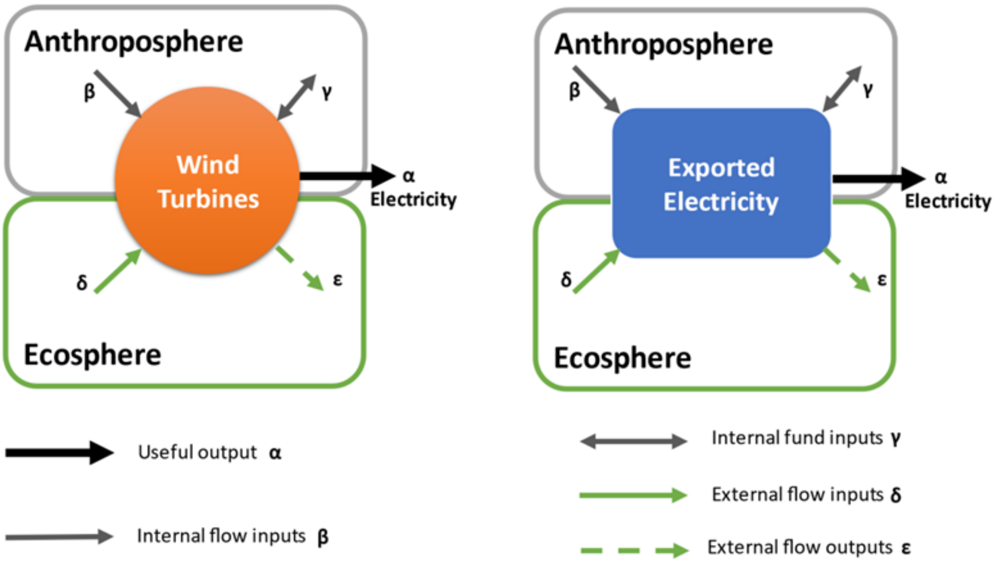

Figure 5.1. Examples of unitary (left) and extensive (right) descriptions of processors. Source: Adapted from Di Felice et al. (2019).

Each processor describes two profiles of inputs and outputs representing a nexus pattern associated with a metabolic element: (i) internal flows and internal funds divided into inputs “coming from” and outputs “going to” the rest of the metabolic network; and (ii) external primary flows divided into inputs “coming from” and outputs “going to” the environment. As a result, we have five types of quantities to be considered:

i. Internal flow inputs: flows under human control coming to the processor from the anthroposphere (the rest of society). They include secondary inputs like electricity from the grid used in a nuclear plant or beef consumed within a household.

ii. *Internal fund inputs:* funds under human control provided by the anthroposphere used in the represented process. Examples include the land on which a power plant is built or the working hours dedicated to a dairy farm.

iii. *Processor-generated output:* the processor's production representing its valuable function, such as the electricity generated by a nuclear plant or the milk production in a dairy farm.

iv. *External flow inputs:* flows extracted from the ecosphere and entered into the process. They consist of primary flows such as the water abstracted for cooling a nuclear reactor or the fraction of water from lakes and rivers distributed as blue water for irrigation.

v. *External flow outputs:* flows released into the ecosphere by the metabolic processes, e.g. GHG emissions or pesticide residues.

The conceptual difference between funds and flows lies in the fact that flows are either produced by funds or extracted from stocks[19]. They establish a link between funds and stocks to processes. Funds remain stable (in size and characteristics) during the duration of the analysis and are among the different metabolic elements. They have a finite supply and sink capacity that must be maintained and respected. Critical is the case of ecological funds in the ecosphere that can be damaged by excessive exploitation. Consequently, the sustainability of social-economic systems is externally constrained by the limits imposed by the ecosphere, i.e. the availability of funds and stocks. Examples include the depletion of crude oil stock on the supply side or the excessive release of GHG into the atmosphere on the sink side. In turn, inside the society, funds in the anthroposphere are shared among processes. This entails an opportunity cost of each activity within a zero-sum game budget, determining the existence of an internal constraint. Therefore, the possibility of utilising internal societal funds in a given processor, i.e. the amount of labour and land, depends on the allocation being used by

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[19] Drawing on Georgescu-Roegen (1971), the distinction between flows that originate from funds and those that arise from stocks has profound implications for sustainability. The use of a fund requires a duration. This duration is determined by the physical structure of the fund (e.g. a cow, a fund element, has to be milked for half an hour to get a litre of milk). Moreover, if the fund can repair and reproduce itself, the resulting flow can be considered renewable. On the contrary, a stock can be viewed as an accumulation of flows and decumulated most of the time at will. Therefore, the input derived from a stock-flow process is a non-renewable resource.

others. For instance, the amount of land for agriculture may be limited by the space used for urban development.

When using metabolic processors, it is essential to differentiate between the characterisation of structural types, which are theoretical elements like “off-shore oil extraction platforms in Europe”, and instances of these structural types, which are specific realisations of these types, such as a particular oil extraction platform. The metabolic characterisation of structural types relies on benchmarks’ values (technological coefficients), available in reports. The metabolic characterisation of instances of structural types is done at a local scale using direct measurement coefficients. In this chapter, the primary rationale will be comparing the expected values associated with quantifying the externalisation with the observed values related to specific instances of the system under analysis.

5.3.2. Relation to metabolic processors across hierarchical levels to account for externalisation.

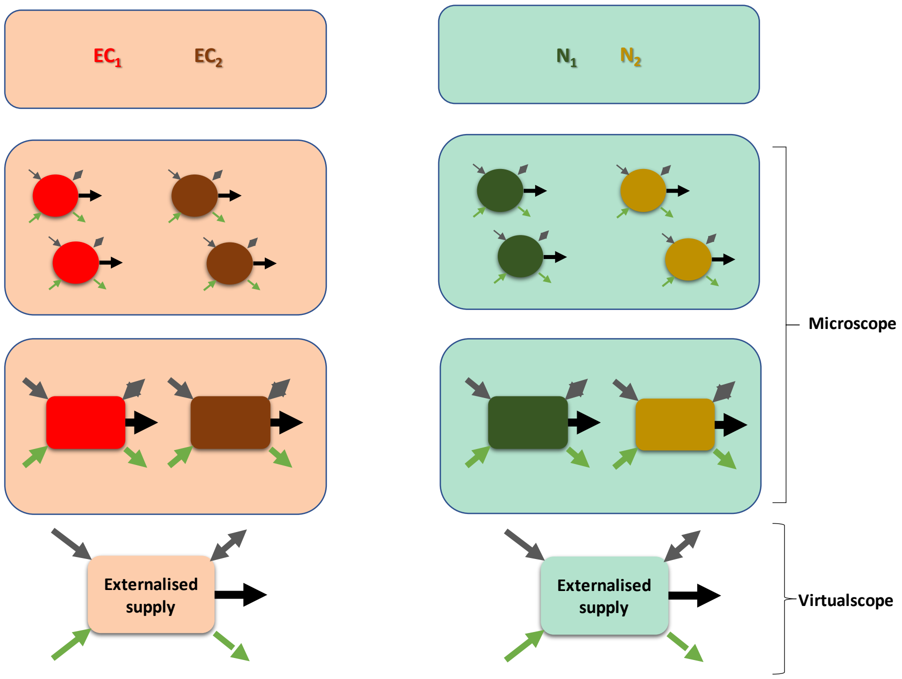
A hierarchy is “a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem” (Simon, 1962, p. 468). For example, energy and food systems can be divided into hierarchical levels consisting of structural and functional processors. In this case, the hierarchy organisation is nested, as lower-level components are aggregated into higher-level ones. For instance, wheat, rice and barley production can be aggregated into cereals. The production of cereals, oilseeds and vegetables can be aggregated into the production of cultivated plants. And the production of plants and animals can be aggregated into agricultural production. Similarly, different technologies that produce electricity in the mix (e.g. nuclear, solar, wind) can be aggregated with the consumption of a determined quantity of electricity (e.g. imported electricity) at a higher level.

Another method of aggregation in sequential pathways refers to the characterisation of sequences of operations taking place at the same level to fulfil a given function. Sequential pathways are chains of processes observed at the same scale, connected by a material entailment —e.g. the output of the “oil extraction” processor is used as an input for the “refinery” processor whose output is used as an input by the “oil products distribution” processor. Or the output of the “production of feed” processor is used as an input for the “industrial production of pig meal” processor.

A set of expected relations between processors can be used to account for externalisation based on the resulting characteristics of structural and functional types. We refer to externalised processes as energy or food processes outside the geographical boundaries of the system under study that are needed (and used) to support the system's endosomatic and exosomatic metabolism. These processes make imports available and complement local production processes that generate local supply inside the system, giving rise to metabolic requirements for accomplishing different societal functions (e.g., heating and cooling, tourism and restoration, or education).

The adoption of metabolic processors and their connections in hierarchical and sequential pathways allows for a kind of analysis that integrates different levels of observation: (i) the microscope is used to analyse the various externalised processes of production and examine the inputs and outputs profile at each step of the sequential pathways associated to a particular functional supply system (e.g. biophysical requirements for the production of electricity in a coal power plant); and (ii) the virtualscope serves the purpose of assessing the total requirements of end uses (secondary input flows and societal funds) and primary flows (inputs and outputs) connecting processors in hierarchical pathways to account for the factors of production that have been used externally to produce the imported goods (e.g. biophysical requirements of the imported electricity based on the aggregation of the different inputs and outputs associated to the various externalised processes involved in producing this secondary input). This analysis contributes to determining the level of externalisation (openness) of the energy and food sectors. In addition, these two levels can relate to the macroscope, reflecting on the actual distribution of nexus elements (in the form of funds and flows) across the different societal sectors within the analysed system (e.g. how much land and water is used in the local energy or agricultural sectors) once externalised supply eases the tension between local supply and local consumption. The microscope follows the logic of nexus analyses when studying the relations among biophysical elements that tend to be considered isolated (e.g. energy for water when studying the energy requirements of a desalination plant or water for energy when investigating the water requirements of cleaning solar PV panels (Yoon et al., 2022). The macroscope is related to biophysical budget analyses when studying the annual biophysical constraints of a metabolic system —e.g. the competition for limited land and water resources (Cadillo-Benalcazar et al., 2021) or human time between societal compartments (Manfroni et al., 2021). The virtualscope, for its part, looks at how metabolic systems reduce their local socio-environmental pressures and impacts through trade with other territories (Hornborg, 2009; Renner et al., 2020).

Since externalisation can be calculated recursively (i.e. what is embodied in the embodied), a chosen truncation is needed (Chapman, 1974; Giampietro et al., 2013). In this case, direct imports are energy and food commodities imported directly, while indirect imports are those required to produce the direct imports (e.g. direct petroleum products imports vs the oil needed to produce these imports or meat directly imported vs the indirect feed necessary to make this meat). Both direct and indirect imports are aggregated into an "externalised" category, and the inputs and outputs associated with all externalised processes are grouped, leading to externalised inputs and outputs of the energy and food sectors. Figure 5.2 synthesises the methodological steps.



Step 1: Quantification of direct imports of energy carriers (e.g. electricity and oil products) and nutrients (e.g. animal and plant food) of the system under study

Step 2: Determination of the metabolic processors associated with the production of imports. Boundaries: extraction of primary energy sources needed to produce imported energy carriers (e.g. coal as an indirect import to produce imported electricity) and feed required to have imported meat (e.g. grains as an indirect import to make the imported poultry meat)

Step 3: Aggregation of the inputs and outputs of the externalised processes based on which direct imports of energy carriers and nutrients they produce

Step 4: Aggregation of the inputs and outputs of all externalised processes embodied in energy and food imports leading to externalised inputs and outputs of the energy and food sector of the system under study

Figure 5.2. Methodological steps for calculating the externalised inputs and outputs of the energy and food sectors. Source: Own elaboration.

It is important to note that the externalisation analysis using metabolic processors requires a clear definition of: (i) the actual size of the imported flows (e.g. the secondary inputs, such as different energy carriers or food items); (ii) the structural mix of production processes associated to the imported flows, i.e. the set of connections of metabolic processors in sequential and hierarchical pathways (e.g. what percentage of the imported electricity is generated outside the system boundaries by a hypothetical coal power plant, and how much of the coal used in this hypothetical plant is extracted by open-pit mining and how much by underground mining); and (iii) the inputs and outputs associated to different processes, i.e. the characterisation of the metabolic performance of structural types based on expected values from benchmarks or technical coefficients (e.g. how much water and labour are required by a theoretical hydroelectric plant to produce one MJ of electricity or by a meat production system to produce one tonne of beef).

5.4. Boundaries for the Andorran case study.

Data refer to the year 2019. To simplify the model, the transport, transmission, and distribution of energy carriers and the transportation of food commodities are not considered. The focus solely centres on the production and consumption of energy carriers and food items within the geographical boundaries of Andorra.

The main features of Andorra's exosomatic and endosomatic metabolism are analysed using an internal EUM. This tool allows a quantitative representation of the different flows metabolised inside the anthroposphere to perform various societal functions associated with maintaining a set of local social practices. In addition, externalisation is assessed using the values associated with two EUM (local and externalised), characterising viability factors of the Andorran energy and agricultural systems, and two EPM (local and externalised), describing feasibility factors of Andorran the energy and agricultural system. Table 5.1 summarises the observable attributes considered in this study.

The diagnosis analysis adopts a top-down approach, similar to that used in Chapter 4, but this time also incorporates food requirements. The externalisation analysis is constructed by characterising externalised processes using structural types represented by specific metabolic processors. This assessment allows a comparison between the biophysical requirements, i.e. the observable attributes of Table 5.1, embodied in the energy and food products imported, and the local use of these attributes within the energy and agricultural systems of Andorra. These local values are derived from the performance of specific instances of structural elements within Andorra's geographical boundaries, with the corresponding data sourced from statistical reports and other relevant sources.

Table 5.1. Observable attributes considered for the quantitative representation of Andorra's metabolic performance and the externalisation analysis.

Analysis	***Observable attribute***	***Definition and units***
Diagnosis	HA (Human Activity)	Time in millions of hours (Mh) devoted to each level of analysis.
	EC (Energy Carrier)	Amount of type of energy (i.e. electricity, heat, or fuel) used in each level of analysis (GWh for electricity and TJ for thermal energy as heat or as fuel for transportation).
	GER (Gross Energy Requirement)	Equivalence in TJ applying the Partial Substitution Method (Giampietro et al., 2013) where MWh of electricity is converted into TJ and multiplied by 2,61, TJ of heat is multiplied by 1,10, and TJ of fuels is multiplied by 1,38.
	GFS (Gross Food Supply)	TJ entering the domestic food supply chain.
	MR (Metabolic Rate)	Amount of flow (GER or GFS) per unit of human activity in each level of analysis (MJ/h or kcal/h).
Externalisation	Labour (internal fund input)	Labelled as human activity (HA), measured in hours (h). Only direct employment is considered (i.e. operation and maintenance activities).
	Land Use (internal fund input)	Area of land (in hectares) devoted to crop production or the land occupied by a power plant or installation.
	Water (external flow input)	Water (in cubic hectometres) is water withdrawal in the energy sector. Concerning the food sector, water is blue water, i.e., the fraction of water distributed for irrigation, service water, and animal drinking water.
	GHG emissions (external flow output)	GHG emissions converted into tCO_2 equivalent. Only emissions related to enteric fermentation and manure management are considered in the agricultural sector.

Data for energy and food externalised processes are sourced from the nexus databases developed within the MAGIC project (Giampietro et al., 2020). These databases, available on Zenodo (Cadillo-Benalcazar and Renner, 2020; Di Felice, 2020), provide comprehensible information on inputs and outputs scaled by unitary outputs (e.g. hours of human activity scaled by kilogram of coal extracted). This data from unitary processors has been scaled up by the energy and food commodities imported into Andorra. Data on externalised processes include the extensive output and structural mix information (e.g., what amount of imported energy is generated in a combined cycle power plant, what percentage of the gas used in that hypothetical power plant is extracted offshore, and how much onshore). Spain and France's electricity generation mixes are considered for imported electricity, Spain's refining mix for oil products, and Spain's technical coefficients of production for agricultural products. For example, the nexus requirements of imported electricity from Spain (Figure 5.3) are calculated by linking primary energy sources (PES) extraction and electricity production processes. In turn, the inputs and outputs of the different supply systems of electricity production are aggregated into the superior hierarchical category of “imported electricity from Spain”. Further details on the database selection process and the aggregation of processors across scales can be found in Appendix B.

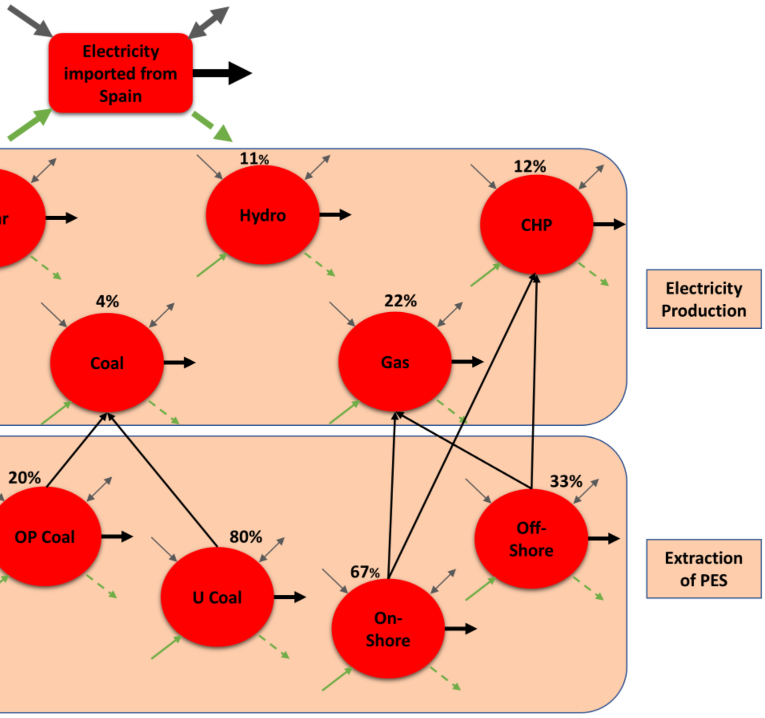


Figure 5.3. Processors’ entanglement to represent the electricity imported from Spain. Source: own elaboration from data from REE (2020) and Di Felice (2020). Nuclear: nuclear plant; Wind: wind turbines; Solar: solar PV; Coal: coal power plant; Hydro: hydropower plant; Gas: natural gas turbines; CHP: combined heat and power; NFE: nuclear fuel element plant; Open pit: open pit uranium mining; In-situ: In-situ leaching uranium mining; OP Coal: open pit coal mining; U Coal: underground coal mining; On-Shore: onshore gas extraction; Off-Shore: offshore gas extraction.

5.5. Results and discussion.

5.5.1. Metabolic performance: a diagnosis from the macroscope.

Table 5.2 synthesises Andorra’s metabolic performance using an internal EUM. As we saw in the previous chapter, Andorra depends on external biophysical elements. Data on HA for 2019 shows that “Other users” (tourists and one-day visitors) represent 24% of the total. In this sense, the SG takes up a significant amount of the time related to tourist activities, needing higher exosomatic energy requirements per hour of work (73.1 MJ/h) than industry or agricultural activities.

Table 5.2. EUM characterising Andorra's exosomatic and endosomatic metabolism.

		Exosomatic metabolism					*Endosomatic metabolism*	
Constituent Components	*Human activity HA (Mh)*	*Electricity E (GWh)*	*Heat H (TJ)*	*Fuel F(TJ)*	*GER[a] (TJ)*	*Exo MR[b] (MJ/h)*	*GFS[c] (TJ)*	*Endo MR[d] (kcal/h)*
N (Andorra)	**969**	**567**	**1 939**	**2 604**	**11 061**	**11.4**	**314**	**77**
N-1								
Households (HH)	650	186	634	2 116	5 371	8.3	314	77
Paid work (PW)	85	381	1 305	488	5 690	66.9	n.a	n.a
Other users	234							
N-2 (PW)								
Agriculture (AG)	1	n.a	n.a	1	1	1.5	n.a	n.a
Industry (ICM)	11	26	35	39	336	30.5	n.a	n.a
Services (SG)	73	355	1 270	448	5 353	73.1	n.a	n.a

[a] Gross energy requirement; [b]Exosomatic metabolic rate; [c]Gross food supply; [d]Endosomatic metabolic rate. Values for the year 2019. Sources: Own elaboration from the Department of Statistics (2019)*, Miquel et al.* (2021)*, and Andorran Government* (2007).

Regarding energy carrier consumption, the HH heavily relies on oil products as fuels (81% of the total fuel consumption). The PW predominantly uses electricity and oil products as heat (67% of total consumption for both energy carriers). Full requirements in GER are distributed evenly between the HH (48%) and the PW (52%). Andorra has an exceptionally high value of the exosomatic metabolic rate in the HH (8.3 MJ/h), considered a proxy of the material standard of living (Velasco-Fernández et al., 2020). As commented in Chapter 4, this value surpasses the EU average of 6.4 MJ/h and is comparable to countries like Canada (8.8 MJ/h) or the USA (10 MJ/h). Andorra's metabolic exosomatic rate at the country level of 11.4 MJ/h resembles the average European level of 17 MJ/h calculated for 2015 in the previous chapter. Finally, its endosomatic metabolic rate for the maintenance of the country's equivalent population is approximately 1 854 kcal/day (equivalent to the value shown in Table 5.2 of 77 kcal/h), approaching neighbouring countries such as Spain, with 1 810 kcal/day (Ruiz et al., 2015).

Importing energy carriers and nutrients is essential for Andorra to ensure the performance of the different social practices associated with its total human activity, meet the mentioned metabolic benchmarks, and focus on the service sector. Concerning the characterisation of Andorra's energy and agricultural sectors, Figure 5.4 illustrates the reliance of Andorra's exosomatic and endosomatic metabolism on externalised processes. The Andorran energy system produced around 20% of its electricity consumption in 2019, while the remaining 80% was imported. Exports to France and Spain were negligible, accounting for around 0.05% of the total electricity produced (FEDA, 2019). Local electricity generation primarily relies on renewable sources, mainly hydropower (75%). Oil products, such as petrol, diesel, and heating fuel used in transport and heating, were also imported. A lower fuel price in Andorra than in its neighbouring countries and the high number of visitors entering the country by car suggest that fuel tourism could have a significant weight in national fuel imports, exceeding metabolic needs and representing an important source of tax revenues (Travesset-Baro et al., 2016).

Regarding the agricultural sector responsible for local food production, extensive farming practices in Andorra involve utilising high mountain pastures during the summer and relocating livestock to warmer lands in the valleys during the winter. Agricultural activities complement livestock rearing (mowing the grass) and mainly focus on self-consumption, except for the production of tobacco intended for export (Komac et al., 2020). Due to the characteristics of the local components and their contribution to local supply, Andorra relies heavily on imported plant and animal-based food products.

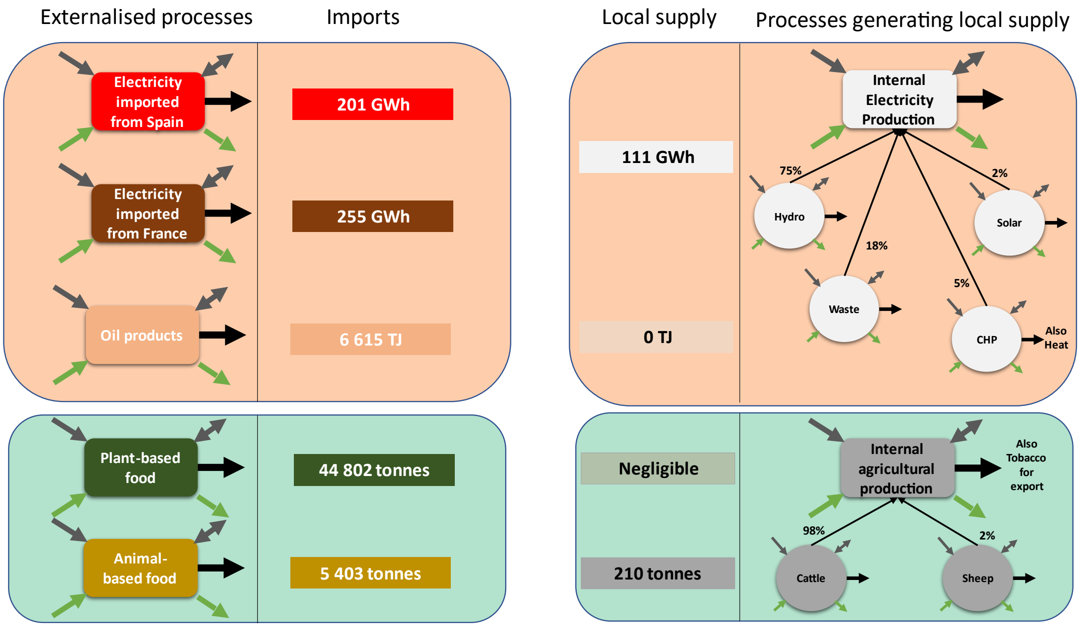


Figure 5.4. Andorra's dependence on externalised processes that produce imports. Source: Own elaboration from data from Miquel et al. (2021) and Agricultural Department (2019).

5.5.2. Characterising externalisation in the energy sector.

Figure 5.5 compares the nexus patterns of inputs and outputs for local exosomatic energy supply with values from the externalised processes generating imports. Since externalised processes are needed for the country's reproduction and maintenance of its identity, these results highlight a significant dependence on other territories concerning: (i) activities related to the production of electricity imported from Spain and France, including PES extraction processes (e.g. gas extraction or uranium mining) and power plant operations; and (ii) activities related to the supply of different petroleum products (i.e. oil extraction and refining). As a result, from this analysis based on the virtualscope, Andorra externalises:

- 7 times the working hours invested locally in its energy sector.
- 40 times the land devoted to producing local electricity.
- 6 times the water abstracted for energy issues.
- 17 times the emissions compared to those generated by the local energy sector.

These assessments contrast with findings for a sample of EU countries. Notably, there is low dependence on virtual labour in the energy sector except for The Netherlands, which externalises three times the working hours invested locally. Also, accounting for the energy sector's externalised carbon emissions raises the EU average's total GHG emissions by only 60% (Ripa et al., 2021).

Among the externalised processes related to the extraction of PES, some are very labour-intensive per unit of output, such as uranium mining. In contrast, others require significant amounts of land (e.g. coal mining) or water (e.g. gas extraction) or generate substantial emissions per unit of output, such as oil extraction. Similarly, among the externalised processes producing energy carriers, such as electricity and oil products, some require high labour per output unit, such as solar photovoltaic systems. Others are land-intensive, such as wind turbines, with significant water demands, such as hydropower, or emitting large quantities of GHG per unit of output, such as coal power plants or refinery processes (see Tables B1 and B2 of Appendix B for details). We can use the microscope to check the various externalised processes associated with a particular supply system. So, electricity imported from France stands out for its significant water requirements, mainly due to nuclear power, which requires non-consumptive water for cooling and temperature control. In turn, electricity imported from Spain is more polluting in terms of GHG than from France due to its generation mix, including coal power plants, natural gas turbines, and combined cycle plants. Besides, this electricity has higher labour and land requirements. Finally, imported oil products rank high in land use, human activity, and emissions generation.

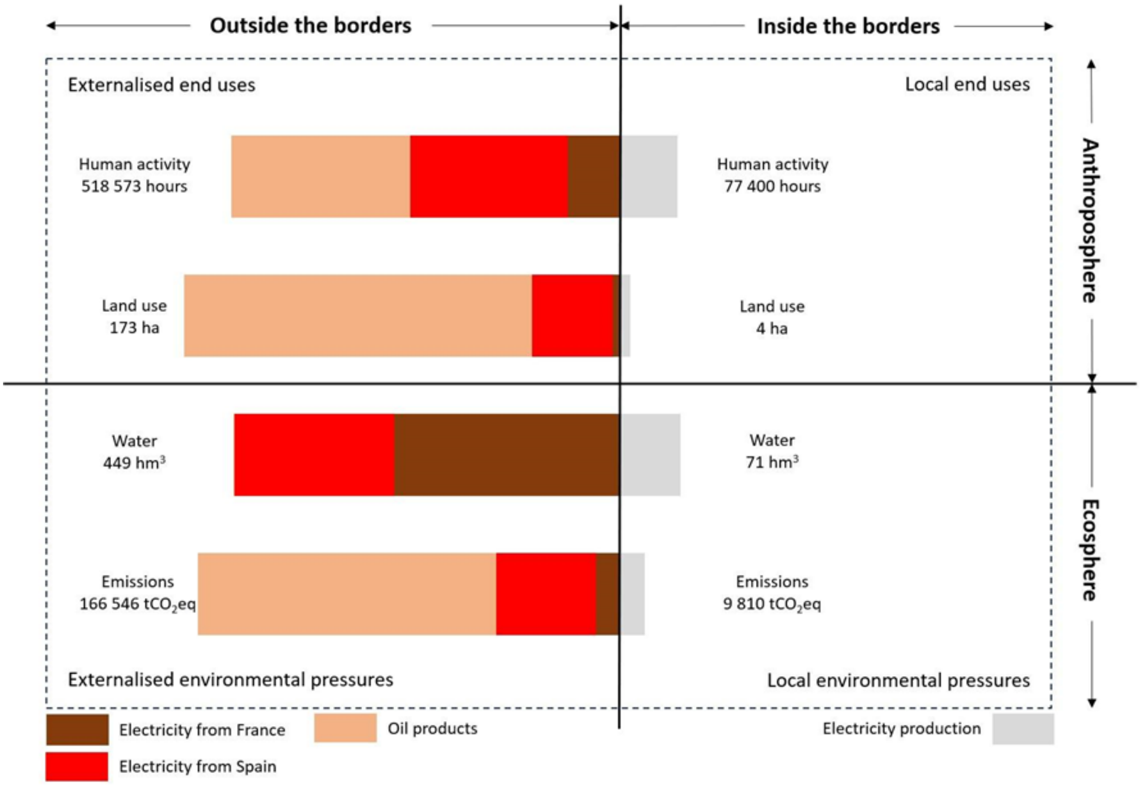


Figure 5.5. Local and virtual externalised values in the Andorran energy sector. Sources and calculations in Appendix B.

A metabolic perspective challenges the notion that local energy production is always better than imported. A determined material standard of living (i.e. desirability constraint) is irremediably linked to feasibility —e.g. water requirements— and viability constraints —e.g. labour requirements. In the case of strong biophysical limits, the standard of living can only be maintained by relying on externalised processes. Therefore, there is an inherent tension between increasing system openness (associated with a greater vulnerability to external factors) and reducing local environmental pressures by importing. In this regard, examining the current allocation of flows and funds within the Andorran system (i.e. considering the macroscope) reveals that the massive externalisation of energy processes has contributed to maintaining a relatively safe, healthy, and clean environment. This solution has avoided the degradation of Andorra's ecological funds, such as forests and meadows covering most of the territory, which would have otherwise been threatened by land-intensive renewable projects and has positioned the country as a tourist destination, specialised in the service sector. These considerations challenge the narrow scope of dominant energy security narratives. These narratives tend to focus on simplified problem definitions (e.g. achieving greater energy sovereignty is good), where causality can be easily discerned, and courses of action can be decided upon (e.g. to increase local electricity generation). However, a biophysical reading from different dimensions shows that win-win solutions are rarely possible. Consequently, the belief that it is possible to increase energy sovereignty without generating pressures on land, water bodies, or market labour should be considered a policy legend (Giampietro and Funtowicz, 2020).

Finally, a perspective that includes externalisation provides a more informed view for deliberation concerning decarbonisation plans. While a significant portion of climate-friendly technologies produce Andorra’s local electricity, oil products associated with extraction and refining activities are entirely imported. These oil products, used as heat or fuel, play a central role in Andorra’s exosomatic metabolism, accounting for 75,5% of total consumption (Miquel et al., 2021). Oil extraction activities are highly polluting, considering emissions, relying on unsustainable stock-flow exploitation of non-renewable resources. Refineries are almost entirely fossil-fuelled. Consequently, oil products’ emissions represent 71% of the total externalised emissions. Figure 5.5 shows that externalised GHG emissions are non-negligible, highlighting the need for decarbonisation policies to consider the system’s openness.

5.5.3. Characterising externalisation in the agricultural sector.

Figure 5.6 compares the nexus patterns of inputs and outputs generating the local supply of endosomatic energy with values from externalised processes generating imports. The analysis based on the virtualscope shows how the endosomatic metabolism of Andorra requires externalising:

- 8 times more work hours compared to the values of their local agricultural system.
- 15 times more land.
- 22 times more water consumption for irrigation.
- 7 times the emissions compared to those generated by local meat production.

Some of the results put Andorra in line with countries like The Netherlands, which also presents high levels of externalisation in the land (14 times) and agricultural labour (7 times) (Cadillo-Benalcazar et al., 2020).

A move to internalise imports for greater food security would increase pressures on local ecosystems. Considering production processes through the microscope (see Table B.15 of Appendix B), cereals require significant land (0.43 hectare/tonne), fruits are intensive in work (38 hours/tonne), and oil-bearing products have high water needs (1 120 cubic metres/tonne). Moreover, results show that imports of animal-based products have more extensive land, water, and human activity requirements than imports of plant-based products (see Tables B.16 and B.23 of Appendix B), supporting other studies indicating the significant environmental impact of animal-based products (D'Odorico et al., 2018).

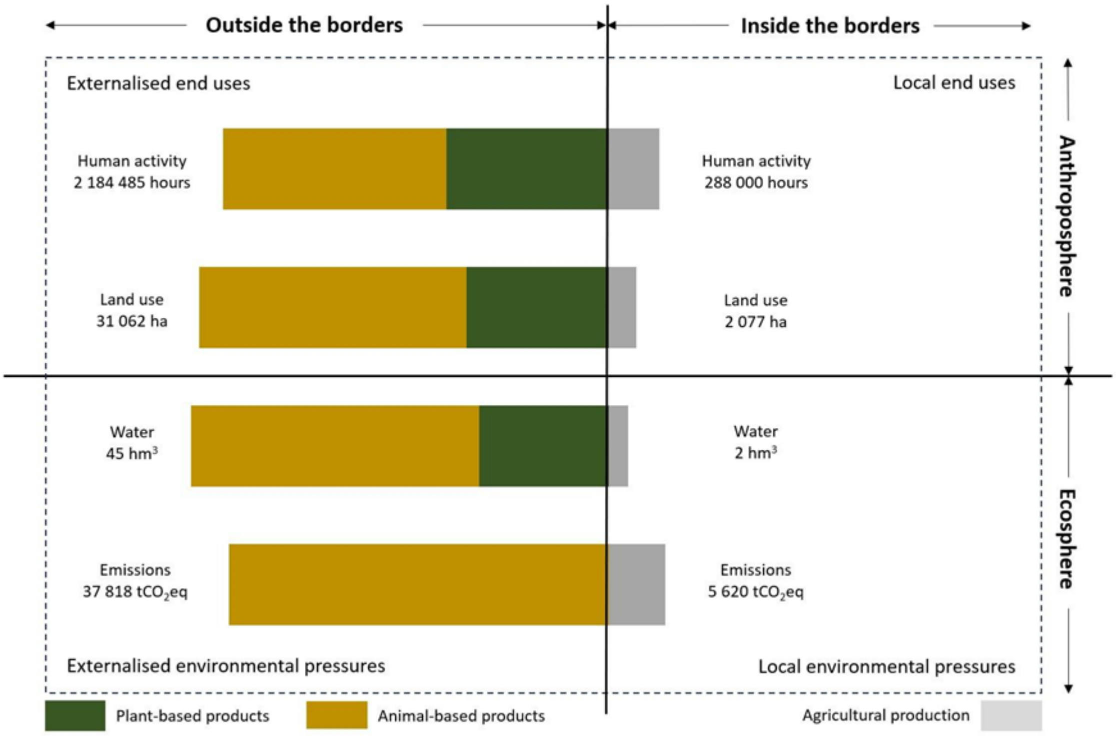


Figure 5.6. Local and virtual externalised values in the Andorran agricultural sector. Sources and calculations in Appendix B.

Regarding the macroscope and microscope indications, a substantial internalisation of food production faces severe feasibility and viability constraints, given the current allocation of production factors in Andorra. There is a shortage of agricultural land in absolute terms (farms already occupy the most fertile and productive areas) but also for competition for alternative land uses due to intense urbanisation and the spaces required to preserve biodiversity (Lluelles and García, 2018). Importing food also allows for the externalisation of labour, reducing tensions in the labour market and allowing

Andorra to specialise in the service sector. Additionally, the agricultural sector in Andorra generates a lower economic return per hour of work than tourism or commercial activities. Meeting the significant blue water requirements of internalising production would result in additional pressures on water basins already stressed by population and urban growth, which will be aggravated by climate change (Travesset-Baro et al., 2022). Moreover, although associated with thermal combustion processes in transport and industry, the internalisation of food production would increase local GHG emissions, which currently represent 1% of the national GHG emissions (Miquel et al., 2021).

Massive outsourcing of commodity production destroys habitats and sets environmental pressures on external environments. This issue poses ethical concerns, particularly concerning animal products. The production of meat is associated with substantial feedstuff requirements. In this study, importing over 5 000 tonnes of meat requires indirectly over 68 000 tonnes of feed products. Animal feed production raises sustainability concerns like deforestation of tropical areas (Carvalho et al., 2019) or displacement of people (Sauer, 2018). Therefore, shifting consumption patterns, significantly reducing meat intake, and minimising food waste would relieve pressures for achieving greater food security while reducing environmental and social conflicts elsewhere.

5.5.4. Limits of the results.

This study's primary objective is to compare the expected values associated with quantifying externalisation to the observed values of the analysed system obtained primarily through reports. This framework relies on a hierarchical organisation and enforced relations across levels. Structural types are aggregated, and their outputs must match those of higher-level functional ones. However, the elusive nature of complex systems calls for caution in any quantitative result (Giampietro et al., 2006). Uncertainty may arise across different levels: first, in assessing the expected set of inputs and outputs related to structural processors, depending on the accuracy of data sources. Second, moving up, uncertainty is tied to the selection of structural group combinations into functional ones.

Concerning the first point, Yoon (2018) highlights challenges in studying nexus relations due to data availability, accessibility, and quality. The datasets used in this analysis result from their authors' efforts and provide an exceptional starting point for realising biophysical studies. Research on the nexus would be a good starting point to foster the discussion on the need for public and quality data. In conclusion, the externalisation results are approximations based on average technical coefficients.

The second point is crucial for food commodities. The variety of food commodities, the complexity of livestock systems, and the diverse options for livestock diets have led to problematic assumptions about expected relations (e.g., which vegetables are included in the different functional groups or which feed types are considered). In this sense, the analysis of food requirements approximates actual needs since not all food imports imported from Andorra have been considered (for instance, alcoholic beverages have been overlooked, and milk and eggs are considered byproducts) and, mainly, some feed categories have been disregarded to avoid problems of double counting (e.g. the accounting of soybean and soybean byproducts such as oil of soybeans). These considerations call for caution when drawing solid conclusions from the results. This type of analysis should not be used within the logic of “evidence-based policies” (i.e. to identify the best policy) but rather within the logic of “quantitative storytelling” (i.e. to assess the robustness of the narratives used to discuss policies). In this different logic, precise measurements of land utilisation are less critical than flagging the severity of import dependence to avoid the existence of strong biophysical constraints.

5.6. Conclusions.

The viability and feasibility of Andorra’s metabolic pattern depends on imports. Moreover, geopolitical concerns have highlighted the importance of energy and food security. Therefore, an externalisation analysis is relevant. Based on MuSIASEM, the approach offers a complex representation of societal metabolism, analysing the dependence of the exosomatic metabolism (associated with energy security) and the endosomatic metabolism (related to the concept of food security) of externalised processes. MuSIASEM integrates information across scales, providing a comprehensive view of countries’ metabolism from the microscale of the technical conversions to the macroscale of the whole country. To do this, transparent assumptions across hierarchical levels, resource types (e.g. primary flows vs secondary inputs), and nexus elements (e.g. water as a flow element and land as a fund element) are essential.

Using relational analysis, the biophysical performance of Andorra’s energy and food systems is characterised by identifying externalised processes across multiple levels. On aggregate terms (i.e. using the virtualscope), our results show the country’s high dependence on other territories. Andorra stands out by externalising seven times the working hours, 40 times the land and six times the water compared to the values of its local energy sector. Moreover, externalised energy processes emit 17 times more GHG emissions than components generating local energy supply. In addition, Andorra uses eight times more human activity, 15 times more land, 22 times more blue water and GHG emissions are multiplied by 7 in relation to the local agricultural system to maintain its endosomatic metabolism. Therefore, Andorra is a classic example of a complex adaptive system that must be open. It relies on trade to preserve and adapt its identity. The approach shifts the analysis focus to externalised production processes using the microscope, observing, for instance, the profile of inputs and outputs of the electricity imported from France and Spain. While the former requires more water, the latter is more polluting in terms of emissions and demands more work and land.

Furthermore, viewing from the macroscope, the metabolic coupling between externalised processes and the local economy reveals a particular configuration of fund and flow elements inside the country. Andorra can specialise in service sector activities and be a tourist destination related to a “pristine nature” only because it externalises massive amounts of labour, land, water, and emissions to other economies. The option of importing enables Andorra to ease internal resource requirements of economic pressures (by avoiding the labour and land required to produce energy and food commodities and therefore overcoming potential viability constraints) and environmental pressures (by avoiding the local use of natural resources and sink capacity and therefore overcoming possible feasibility constraints). This solution exposes the country to economic and environmental shocks beyond its borders and direct control.

Results shed light on decarbonisation policies and ethical concerns, suggesting that more attention should be paid to regulating the system’s openness since externalising displaces environmental deterioration and social conflicts. Findings also highlight the need for indicators beyond mainstream energy policies. Considering endosomatic and exosomatic metabolism allows new policies targeting consumption patterns (e.g. reducing meat consumption) to alleviate pressures and impacts on the ecosphere. On a positive note, Andorra’s intensive metabolic requirements are mitigated by its small size compared to other EU countries.

The holistic perception and representation of the complexity of the relations found in the energy and food systems invite us to overcome the current “silo governance syndrome", i.e. solving one problem at a time while ignoring adverse side effects on other aspects of the sustainability predicament. In this sense, the biophysical accounting presented here emphasises the idea of sustainability as an interweaving of the ecosphere and anthroposphere's funds and flows, rejecting unidimensional visions. Furthermore, it provides insights for policymakers by exposing and exploring burden-shifting and inherent limits associated with the system under analysis, questioning the possibility of some simplistic sustainability options (e.g. a great food or energy sovereignty or rapid decarbonisation) without fundamental tensions in different dimensions of the local funds (e.g. pressures on land or the market labour). Finally, the idea of limits permeates the approach. Suppose human societies are committed to preserving essential elements of their identities (i.e. desirability) in line with environmental (i.e. feasibility) and social (i.e. viability) constraints. In that case, it can only be achieved by an imperative reconfiguring of production and consumption patterns, if not society. Ultimately, sustainability is not a technical question of properly controlling natural resources but a collective social responsibility to control ourselves through adequate institutions.

5.7. Chapter references.

Agricultural Department, 2019. Agricultural and livestock statistics [WWW Document]. https://www.agricultura.ad/estadistiques (accessed 25 March 2023)

Ahl, V., Allen, T.F.H., 1996. Hierarchy Theory. Columbia University Press, New York.

Andorran Government, 2022. El Govern aprova mesures de reducció del consum i d'estalvi energètic d'obligat compliment per al sector empresarial [WWW Document]. https://www.govern.ad/medi-ambient/item/15135-el-govern-aprova-mesures-de-reduccio-del-consum-i-d-estalvi-energetic-d-obligat-compliment-per-al-sector-empresarial (accessed 22 April 2023)

Andorran Government, 2007. Avaluació de l'estat nutricional de la població d'Andorra 2004-2005. Govern d'Andorra, Andorra la Vella.

Badreldin, H.A., Atallah, B., 2021. Global drug shortages due to COVID-19: Impact on patient care and mitigation strategies. Res. Soc. Adm. Pharm. 17, 1946–1949. https://doi.org/10.1016/J.SAPHARM.2020.05.017

Ben Hassen, T., El Bilali, H., 2022. Impacts of the Russia-Ukraine War on Global Food Security: Towards More Sustainable and Resilient Food Systems? Foods 11, 2301. https://doi.org/10.3390/foods11152301

Berkes, F., Colding, J., Folke, C., 2003. Navigating Social-Ecological Systems : Building Resilience for Complexity and Change. Columbia University Press, New York.

Bjørn, A., Chandrakumar, C., Boulay, A.M., Doka, G., Fang, K., Gondran, N., Hauschild, M.Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., Ryberg, M., 2020. Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. Environ. Res. Lett. 15, 083001. https://doi.org/10.1088/1748-9326/AB89D7

BOPA, 2018. Llei 21/2018, del 13 de setembre, d'impuls de la transició energètica i del canvi climàtic (Litecc). Butlletí Oficial del Principat d'Andorra, Andorra la Vella.

BOPA, 2000. Llei d'Agricultura i ramaderia de 22 de juny del 2000. Butlletí Oficial del Principat d'Andorra, Andorra la Vella.

Brouwer, F. (ed), 2022. Handbook on the water-energy-food nexus. Edward Elgar Publishing, Cheltenham.

Cadillo-Benalcazar, J.J., Bukkens, S.G.F., Ripa, M., Giampietro, M., 2021. Why does the European Union produce biofuels? Examining consistency and plausibility in prevailing narratives with quantitative storytelling. Energy Res. Soc. Sci. 71. https://doi.org/10.1016/j.erss.2020.101810

Cadillo-Benalcazar, J.J., Renner, A., 2020. Top-down and bottom-up vegetal and animal product metabolic profiles for 29 European countries (EU27 + United Kingdom + Norway) [dataset] [WWW Document]. Zenodo. https://doi.org/10.5281/ZENODO.3923010 (accessed 10 February 2022)

Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M., 2020. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manage. 271, 110944. https://doi.org/10.1016/j.jenvman.2020.110944

Caprile, A., 2022. Russia's war on Ukraine: Impact on food security and EU response [WWW Document]. Eur. Parliam. Res. Serv. https://www.europarl.europa.eu/RegData/etudes/ATAG/2022/729367/EPRS_ATA(2022)729367_EN.pdf (accessed 13 August 2024)

Carvalho, W.D., Mustin, K., Hilário, R.R., Vasconcelos, I.M., Eilers, V., Fearnside, P.M., 2019. Deforestation control in the Brazilian Amazon: A conservation struggle being lost as agreements and regulations are subverted and bypassed. Perspect. Ecol. Conserv. 17, 122–130. https://doi.org/10.1016/J.PECON.2019.06.002

Chapman, P.F., 1974. Energy costs: a review of methods. Energy Policy 2, 91–103. https://doi.org/10.1016/0301-4215(74)90002-0

Couix, Q., 2020. Georgescu-Roegen's Flow-Fund Theory of Production in Retrospect. Ecol. Econ. 176, 106749. https://doi.org/10.1016/J.ECOLECON.2020.106749

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56. https://doi.org/10.1029/2017RG000591

Department of Statistics, 2019. Demographic, social and economic statistics [WWW Document]. https://www.estadistica.ad/portal/apps/sites/#/estadistica-en (accessed 6 June 2023)

Di Felice, L.J., 2020. Energy systems as holarchies: Complexity and sustainability across scales [dataset] [WWW Document]. Zenodo. URL https://doi.org/http://doi.org/10.5281/zenodo.4271325 (accessed 10 February 2022)

Di Felice, L.J., Ripa, M., Giampietro, M., 2019. An alternative to market-oriented energy models: Nexus patterns across hierarchical levels. Energy Policy 431–443. https://doi.org/10.1016/j.enpol.2018.11.002

European Commission, 2022. REPowerEU Plan (Communication from the Commission to the European Parliament, the European Council, the Council, The European Economic and Social Committee and the Committee of the Regions). COM (2022) 230 final. Brussels.

European Commission, 2020. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions). COM (2020) 381 f. Brussels.

European Commission, 2019. The European Green Deal (Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions). COM(2019) 640 final. Brussels.

European Commission, 2015. Energy Union Package (Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee, the Committee of the Regions and the European Investment Bank). COM (2015) 80 final. Brussels.

European Union Joint Research Center, 2010. International Reference Life Cycle Data System (ILCD) Handbook-General Guide for Life Cycle Assessment. European Union, Luxemburg.

Eurostat, 2023. Euro area annual inflation rate and its main components [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Inflation_in_the_euro_area#Euro_area_annual_inflation_rate_and_its_main_components (accessed 23 March 2023).

Fang, K., Heijungs, R., De Snoo, G., 2013. The footprint family: comparison and interaction of the ecological, energy, carbon and water footprints. Rev. Métallurgie 110, 79–88. https://doi.org/10.1051/metal/2013051

FEDA, 2019. Històric-Forces Elèctriques d’Andorra [WWW Document]. URL https://www.feda.ad/energia-i-meteo/energia/historic (accessed 11 Novembre 2024)

Frischknecht, F., Jungbluth, N., Althaus, N., Doka, G., Heck, T., Hellweg, S., Hirschier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2007. Overview and methodology. Final Report Ecoinvent data v. 2.0. Dübendorf.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2012. Integrating Ecological, Carbon and Water footprint into a “Footprint Family” of indicators: Definition and role in tracking human pressure on the planet. Ecol. Indic. 16, 100–112. https://doi.org/10.1016/J.ECOLIND.2011.06.017

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Giampietro, M., Allen, T.F.H., Mayumi, K., 2006. The epistemological predicament associated with purposive quantitative analysis. Ecol. Complex. 3, 307–327.

https://doi.org/10.1016/j.ecocom.2007.02.005.

Giampietro, M., Aspinall, R.J., Ramos-Martín, J., Bukkens, S.G.F., 2014. Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use. Routledge, London.

Giampietro, M., Cadillo-Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez-Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliverable 4.4, 30 August 2020.

Giampietro, M., Funtowicz, S., 2020. From elite folk science to the policy legend of the circular economy. Environ. Sci. Policy 109, 64–72. https://doi.org/10.1016/j.envsci.2020.04.012

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London. https://doi.org/10.4324/9780203107997

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Societies : Where Economists Fall Short. Routledge, London.

Guinée, J.B., de Koning, A., Heijungs, R., 2022. Life cycle assessment-based Absolute Environmental Sustainability Assessment is also relative. J. Ind. Ecol. 26, 673–682. https://doi.org/10.1111/JIEC.13260

Haberl, H., Schmid, M., Haas, W., Wiedenhofer, D., Rau, H., Winiwarter, V., 2021. Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism. Ecol. Econ. 182, 106949. https://doi.org/10.1016/J.ECOLECON.2021.106949

Heijungs, R., Suh, S., 2002. The Computational Structure of Life Cycle Assessment. Kluwer Academic Publishers, Dordrecht.

Hickel, J., Dorninger, C., Wieland, H., Suwandi, I., 2022. Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015. Glob. Environ. Chang. 73, 102467. https://doi.org/10.1016/J.GLOENVCHA.2022.102467

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.

Hopkins, J.L., 2021. Yes, the global microchip shortage is COVID's fault. No, it won't end any time soon. [WWW Document]. Conversation, 2 June 2021. URL https://theconversation.com/yes-the-global-microchip-shortage-is-covids-fault-no-it-wont-end-any-time-soon-161903 (accessed 3.23.23).

Hornborg, A., 2009. Zero-Sum World. Int. J. Comp. Sociol. 50, 237–262. https://doi.org/10.1177/0020715209105141

Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., Moran, D.D., 2018. Decoupling or delusion? Measuring emissions displacement in foreign trade. Glob. Environ. Chang. 49, 27–34. https://doi.org/10.1016/J.GLOENVCHA.2017.12.006

Koestler, A., 1967. The Ghost in the Machine. Macmillan Co., New York.

Komac, B., de la Parte, I., Riba, L., Pladevall, C., Fanlo, R., Roquet, M., 2020. Pastures comunes i ramaderia a Andorra. Usos, gestió i perspectives. Institut d'estudis Andorrans, Andorra la Vella.

Kovacic, Z., Di Felice, L.J., 2019. Complexity, uncertainty and ambiguity: Implications for European Union energy governance. Energy Res. Soc. Sci. 53, 159–169. https://doi.org/10.1016/J.ERSS.2019.03.005

Krähmer, K., 2020. Are green cities sustainable? A degrowth critique of sustainable urban development in Copenhagen. Eur. Plan. Stud. 29, 1272–1289. https://doi.org/10.1080/09654313.2020.1841119

Kuhn, A., Heckelei, T., 2010. Anthroposphere, in: Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer Berlin Heidelberg, Berlin, pp. 282–341. https://doi.org/10.1007/978-3-642-12957-5_8

Larrabeiti-Rodríguez, J.J., Velasco-Fernández, R., 2022. Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) revisited: synthesizing and updating the theoretical foundations. J. Crit. Econ. 34, 44–68.

Larrabeiti-Rodríguez, J.J., Travesset-Baro, O., Giampietro, M., Velasco-Fernández, R., n.d. Using MuSIASEM to characterise the metabolic pattern of Andorra and its dependence on imports (under review). Ecol. Econ.

Lluelles, M.J., García, E., 2018. Història econòmica d’Andorra, segles XX-XXI. Universitat d’Andorra, Sant Julià de Lòria (Andorra).

Lotka, A.J., 1925. Elements of Physical Biology. Williams & Wilkins Company, Baltimore.

Louie, H.A., 2010. Robert Rosen’s anticipatory systems. Foresight 12, 18–29.

Manfroni, M., Velasco-Fernández, R., Pérez-Sánchez, L., Bukkens, S.G.F., Giampietro, M., 2021. The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth. Ecol. Econ. 190, 107183. https://doi.org/10.1016/J.ECOLECON.2021.107183

Martin, N., Talens-Peiró, L., Villalba-Méndez, G., Nebot-Medina, R., Madrid-López, C., 2023. An energy future beyond climate neutrality: Comprehensive evaluations of transition pathways. Appl. Energy 331, 120366. https://doi.org/10.1016/J.APENERGY.2022.120366

Matuštík, J., Kočí, V., 2021. What is a footprint? A conceptual analysis of environmental footprint indicators. J. Clean. Prod. 285, 124833. https://doi.org/10.1016/J.JCLEPRO.2020.124833

Miquel, C., Cuyàs, M., Boneta, A., 2021. Cuarto informe bianual de actualización de Andorra ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Govern d’Andorra, Andorra la Vella.

Moreno, C., Chassé, D.S., Fuhr, L., 2015. Carbon Metrics: Global Abstractions and Ecological Epistemicide. Heinrich Böll Foundation, Berlin.

OECC, 2021. Estratègia energètica nacional i de lluita contra el canvi climàtic 2020-2050. Oficina de l’Energia i el Canvi Climàtic, Andorra la Vella.

OECD, 2011. Towards green growth. Organisation for Economic Co-operation and Development, Paris.

Peng, S., Zhang, W., Sun, C., 2016. ‘Environmental load displacement’ from the North to the

South: A consumption-based perspective with a focus on China. Ecol. Econ. 128, 147–158. https://doi.org/10.1016/J.ECOLECON.2016.04.020

Red Eléctrica de España (REE), 2020. El sistema eléctrico español 2019. Madrid.

Rees, W.E., 1999. The built environment and the ecosphere: a global perspective. Build. Res. Inf. 27, 206–220. https://doi.org/10.1080/096132199369336

Rees, W.E., 1992. Ecological Footprints and Appropriated Carrying Capacity: What Urban Economics Leaves Out. Environ. Urban. 4, 121–130.

Rees, W.E., Wackernagel, M., 1996. Urban ecological footprints: Why cities cannot be sustainable – and why they are a key to sustainability. Environ. Impact Assess. Rev. 16, 223–248.

Renner, A., 2020. Supercritical Sustainability. A Relational Theory of Social-Ecological Systems with Lessons from a Disenfranchised European Primary Sector. Autonomous University of Barcelona.

Renner, A., Cadillo-Benalcazar, J.J., Benini, L., Giampietro, M., 2020. Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. Ecosyst. Serv. 46, 101195. https://doi.org/10.1016/j.ecoser.2020.101195

Ripa, M., Di Felice, L.J., Giampietro, M., 2021. The energy metabolism of post-industrial economies. A framework to account for externalization across scales. Energy 214, 118943. https://doi.org/10.1016/j.energy.2020.118943

Ripa, Maddalena, Di Felice, L.J., Giampietro, M., 2021. The energy metabolism of post-industrial economies. A framework to account for externalization across scales. Energy 214, 118943. https://doi.org/10.1016/j.energy.2020.118943

Roca-Jusmet, J., Padilla-Rosa, E., 2021. Globalisation and responsibility in the ecological problems. J. Crit. Econ. 31, 1–18.

Ruiz, E., Ávila, J.M., Valero, T., Pozo, S. Del, Rodriguez, P., Aranceta-Bartrina, J., Gil, Á., González-Gross, M., Ortega, R.M., Serra-Majem, L., Varela-Moreiras, G., 2015. Energy Intake, Profile, and Dietary Sources in the Spanish Population: Findings of the ANIBES Study. Nutrients 7, 4739–4762. https://doi.org/10.3390/NU7064739

Sauer, S., 2018. Soy expansion into the agricultural frontiers of the Brazilian Amazon: The agribusiness economy and its social and environmental conflicts. Land use policy 79, 326–338. https://doi.org/10.1016/J.LANDUSEPOL.2018.08.030

Simon, H.A., 1962. The Architecture of Complexity: Hierarchic Systems. Proc. Am. Philos. Soc. 106, 467–482. https://doi.org/10.2307/985254

Sorman, A.H., 2015. Societal Metabolism, in: D'Alisa, G., Demaria, F., Kallis, G. (Eds.), Degrowth: A Vocabulary for a New Era. Routledge, New York.

Tollefson, J., 2022. What the war in Ukraine means for energy, climate and food. Nature 604, 232–233. https://doi.org/10.1038/d41586-022-00969-9

Travesset-Baro, O., Domènech, M., Pesado, C., Pons, M., 2022. Evolución de los usos de los recursos hídricos y posibles tensiones bajo escenarios de cambio climático en Andorra. Andorra la Vella.

Travesset-Baro, O., Gallachóir, B.P.Ó., Jover, E., Rosas-Casals, M., 2016. Transport energy demand in Andorra. Assessing private car futures through sensitivity and scenario analysis. Energy Policy 96, 78–92. https://doi.org/10.1016/J.ENPOL.2016.05.041

Tukker, A., de Koning, A., Owen, A., Lutter, S., Bruckner, M., Giljum, S., Stadler, K., Wood, R., Hoekstra, R., 2018. Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade: Current State and Recommendations. J. Ind. Ecol. 22, 585–598. https://doi.org/10.1111/JIEC.12716

UNEP, 2011. Decoupling Resource Use and Environmental Impacts from Economic Growth. United Nations Environment Programme, Paris.

Vanham, D., Leip, A., Galli, A., Kastner, T., Bruckner, M., Uwizeye, A., van Dijk, K., Ercin, E., Dalin, C., Brandão, M., Bastianoni, S., Fang, K., Leach, A., Chapagain, A., Van der Velde, M., Sala, S., Pant, R., Mancini, L., Monforti-Ferrario, F., Carmona-Garcia, G., Marques, A., Weiss, F., Hoekstra, A.Y., 2019. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. Sci. Total Environ. 693, 133642. https://doi.org/10.1016/J.SCITOTENV.2019.133642

Wang, M., Huo, H., Arora, S., 2011. Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context. Energy Policy 39, 5726–5736. https://doi.org/10.1016/J.ENPOL.2010.03.052

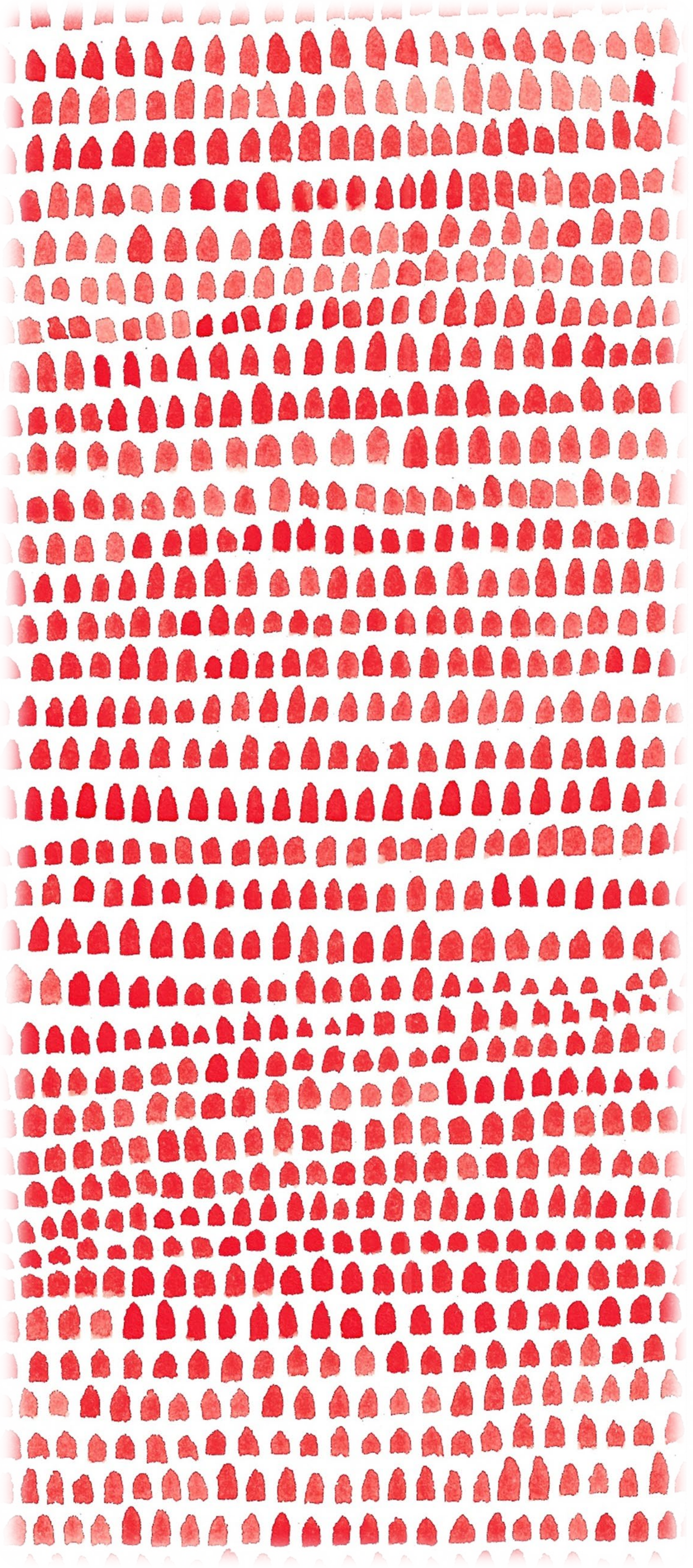
Weber, C., Matthews, D., Venkatesh, A., Costello, C., Mathews, S., 2009. The 2002 US Benchmark Version of the Economic Input-Output Life Cycle Assessment (EIO-LCA) Model.

Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. Ecol. Econ. 61, 15–26. https://doi.org/10.1016/J.ECOLECON.2006.12.003

Yoon, H., 2018. A Review on Water-Energy Nexus and Directions for Future Studies: From Supply to Demand End. Doc. D’Anàlisi Geogràfica 64, 365–395. https://doi.org/10.5565/rev/dag.438

Yoon, H., Sauri, D., Rico, A., 2022. The water-energy nexus in hotels and recreational activities of a mass tourism resort: the case of Benidorm. Curr. Issues Tour. 25, 592–610. https://doi.org/10.1080/13683500.2021.1893283

Chapter 6



6. Narratives matter, too: analysis of critical issues in the Andorran sustainable development policy domain from a metabolic perspective.

> "Las historias. Los relatos.
> El marco narrativo.
> Es necesario entender su importancia
> para llegar al fondo de lo que realmente
> está sucediendo.
> Porque, en su raíz,
> toda esta riña entre formas de ver el mundo
> no trata de números,
> trata de historias"
> Paul Kingsnorth[*].

6.1. Introduction.

It is well known that when dealing with complex issues, how we describe and frame a problem determines the kinds of solutions and answers we can consider (Rittel and Webber, 1973). Complexity can be defined as the presence of multiple non-reducible representations of a system, uncovering the coexistence of different possible perceptions of it across different scales (Ahl and Allen, 1996). It poses the epistemic challenge of irreducible pluralism, as complex systems can only be modelled in a specific way by losing relevant information. Recognising complexity means acknowledging the presence of incommensurability of values (Munda, 2008), which refers to the coexistence of contrasting and legitimate values, perceptions, and interests among social actors —social incommensurability— and the impossibility of reducing the different useful representations into a single quantitative model —technical incommensurability. Moreover, sustainability issues are not only complex (involving an analysis across multiple scales and dimensions) but often require urgent action that, in turn, entails the ability to handle a pluralism of concerns (Kates et al., 2001). In a broad sense, governance of sustainability issues is about the policy and decision-making processes in a context of high uncertainty and complexity (Kovacic, 2015).

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[*] Extract belonging to Kingsnorth, P. (2019). *Confesiones de un ecologista en rehabilitación*. Errata Naturae, Madrid, p. 68.

All these considerations were contemplated in Chapter 3 when discussing biosemiotics. Human societies use recorded information to build and organise knowledge for guiding action, where the social part of a social-ecological system carries out the role of interpretant in the semiotic process. In this way, the society organises itself, guides action, and learns from the experience of interacting with the context to reproduce and adapt. In this process, value systems are an essential part of human societies, and handling contrasting but legitimate values in society represents a significant challenge (Giampietro, 2021). In such a situation, we can get into a dangerous impasse: the selection and prioritisation of the different legitimate concerns in society will determine the choice of useful knowledge claims supported by scientific evidence. However, the scientific evidence supporting the claims will only refer to the chosen preanalytical perception of the problem. This choice reflects values and feelings and does not have a scientific basis. For this reason, politics and power play a crucial role in determining the human condition (Arendt, 1959). Existing power relations among storytellers —with different perceptions about what must be sustained and how— will be the ultimate determinant of the final choice of the analysis (i.e. a set of knowledge claims). Therefore, any discussion over sustainability entails a political or ideological dimension that must be explicitly acknowledged as a preanalytical choice. Because agendas are often politically and ideologically constructed by stakeholders and special interest groups (Head, 2022; Russell et al., 2020), defining priorities over competing narratives associated with different preanalytical decisions can lead to “hegemonization”, an unfair choice of narratives (Funtowicz and Ravetz, 1994) that usually lead to “hypocognition” (Lakoff, 2010), i.e. a simplistic framing that omits essential aspects to be considered for adaptation and sustainability.

Building on the premise above, the utility of societal metabolism accounting must be enhanced by making it part of a more comprehensive sustainability assessment, with the goal of considering, in the first place, how issues have been framed. In this regard, a novel approach called Quantitative Storytelling[20] (QST) (Giampietro et al., 2020), as part of the MuSIASEM approach, has been conceived as a possible way to analyse the selecting narratives in the framing of a given policy problem while checking the relevance of indicators and proposed solutions used in the analysis of the sustainable development domain. The QST’s primary goal is to reflect on the existence of alternative knowledge

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[20] Developed in the EU Project “Moving Towards Adaptive Governance in Complexity: Informing Nexus Security — https://magic-nexus.eu/

claims belonging to alternative frames that have been overlooked or ignored to inform sustainability policy (Giampietro and Bukkens, 2022)

In this Chapter, I use a QST approach to identify possible problems not covered ("out of sight, out of mind") in the conventional frame used in Andorra's political discourse regarding the transition to a more sustainable development. The main goal is confronting this conventional frame (i.e. the original analysis associated with a given set of narratives related to relevant concerns to be addressed, the display of particular policies and the use of specific indicators) with an alternative framing (i.e. different storytelling) using the metabolic approach developed in this thesis. This alternative framing is associated with an alternative analysis carried out from a different perspective (i.e. the field of non-equilibrium thermodynamics). This different perspective suggests the adoption of different policies and using other indicators. In this way, new insights may emerge by comparing non-equivalent approaches (i.e., the conventional vs the metabolic) associated with different pre-analytical choices and different representations in the scientific sphere, contributing to a better-informed discussion about the current policy discourse in the sustainability domain.

This comparative analysis is particularly relevant in the current sustainability crisis. The legitimation imperative of the state intimately tied to increasing material abundance and well-being (Hausknost, 2020) makes green growth strategies (OECD, 2011; World Bank, 2012) the only plan for reducing the systemic unsustainability of society's metabolism. This plan promises the maintenance of economic growth, the massive expansion of renewable energy technologies, the electrification of fossil uses and technological development that will promote efficiency. However, when implemented, this strategy may face different constraints and risks aggravating other facets of the socio-ecological crisis (Prats et al., 2016). For this reason, an alternative diagnosis is essential, answering the question: Is available information, referring to different scales and dimensions, adequately integrated into the sustainability policy-making process?

The discussion that will take place in the following pages must be understood in a framework of post-normal science (Funtowicz and Ravetz, 1993), encouraging a more humble and reflexive approach to policymaking linked to the existence of incommensurability of values. Under this approach, there is no optimal solution to the problem, and it is impossible to eliminate large doses of uncertainty from the analysis. It is also impossible to make predictions and control to achieve desired futures. On the other hand, this approach can help a reflection on what can go wrong if we implement a particular policy or use a specific indicator. Therefore, this QST approach does not claim to provide uncontested “facts” to the deliberation process over sustainability policies. Instead, it helps to understand the nature of problems and potential implications of the proposed solutions using more than one lens at a time.

The rest of the Chapter is structured as follows: Section 6.2 analyses the different narratives used in the political discourse in the Andorran sustainable development domain. Section 6.3 considers relevant elements in the policies mentioned above, contrasting what is expected in the conventional narrative with alternative knowledge claims obtained from a metabolic perspective. The Chapter closes in section 6.4 with some conclusions and final considerations.

6.2. Policy narratives in Andorra.

To understand concerns about the framing of sustainability policies, Giampietro (2018) distinguishes three types of interrelated policy narratives:

- Justification narratives: They identify relevant concerns to be addressed and answer the question, “Why is a given policy or innovation needed in the first place?”
- Normative narratives: They determine the solutions to be implemented, i.e. the strategies and tactics to be adopted, answering the question “What should be done?”
- Explanation narratives: They operate at a lower level of abstraction, specifying the conditions under which different goals should be pursued and answering the question “How should it be done?”.

To this taxonomy of narratives, useful in mapping relations between policy narratives, Di Felice et al. (2021a) add one last kind of narrative that includes a positionality dimension, carrying information about who the narrative is generated by and for what purpose. They distinguish between dominant narratives and alternative narratives. In this logic, dominant narratives are those generated within centres of power, wielding hegemonic power, mirroring the prevailing values of the status quo, and often presented as politically neutral (Foucault, 2005). They have the remarkable capacity to marshal extensive resources —material, moral, organisational, human and cultural—

thus reinforcing their social dominance and influence (Mcadam et al., 2003). Alternative narratives are more decentralised, generated independently from multiple sources, and perceived as politicised due to their challenge to the status quo. We can understand dominant and alternative narratives, such as those of the highest level, like centres of gravity on which the rest of the narratives orbit.

These generic narratives can be applied to the case of Andorra. Table 6.1 summarises the narratives identified within the context of the country's sustainable development policy discussion, based on an analysis of the primary law that serves as the foundation for Andorra's sustainability policies (BOPA, 2018) and a comprehensive report for the UNFCCC (Miquel et al., 2021). These sources were selected due to their relevance and critical role in shaping Andorra's approach to sustainability.

Table 6.1. Analysis of different narratives framing Andorra sustainability policy.

Type of narrative	***Content***
Dominant narrative	There is no contradiction between economic growth and ecological sustainability. The current capitalist system oriented towards accumulation and growth should be reproduced, and our current lifestyles should be maintained. Ecological sustainability can be achieved by only changing technologies (e.g., renewable energies) or individual behaviour (e.g., using electric vehicles in private mobility).
Justification narrative	Climate change poses a greater collective risk. Its impacts are already confirmed, costly, and will increase as global temperatures rise.
Normative narrative	We must decarbonise the economy, achieve a carbon-neutral society by 2050, adapt to climate change, and increase resilience. We must also reduce the energy system's vulnerability by improving energy sovereignty, promoting economic growth, and encouraging the active role of consumers.
Explanation narratives	-Reduce energy intensity by at least 20% in 2030 and 30% in 2050 compared to base year 2010. -Reduce annual greenhouse emissions about a business-as-usual scenario (BAU) by at least 37% in 2030. -Increase national electricity production to 33% of the final demand by 2030 and 50% by 2050 and ensure the percentage of energy from renewable sources (wind, solar, biomass, biogas, hydroelectric, etc.) concerning national electricity production is not less than 75%. -Increase the percentage of electric vehicles in the national vehicle fleet to 20% by 2030 and 50% by 2050. -Promoting the circular economy within waste management.

Source: Own elaboration from BOPA (2018) and Miquel et al. (2021).

Predictably, Andorra's narratives in the sustainable development domain align with those of other European countries. The country joins with global aspirations of the UN 2030 agenda and the associated SDG (UN, 2015) and has ratified high-level sustainability policies such as the Paris Agreement (UNFCCC, 2015). For this reason, many of the relevant issues found in the narratives of the conventional approach that will be confronted from a metabolic perspective in the next section can be found in studies for the UE (Giampietro and Bukkens, 2022). However, I aim to contextualise by presenting some numerical figures concerning the Andorran case.

6.3. Relevant issues in the sustainability discussion.

6.3.1 The narrative of efficiency as a panacea.

From the conventional frame, it is believed that reducing energy intensity (measured as energy units/monetary units) is a valid indicator of sustainability improvement. This belief is part of a set of narratives in the energy policy influenced by conventional economics concerning the idea that increases in "efficiency" or reductions of "intensity" —to use less energy for the same level of output— are effective solutions to reduce the consumption of energy carriers (used as electricity, heat or fuel as explained in Chapter 4), and related emissions (Dunlop, 2022).

This conviction persists despite Sadi Carnot's early warnings or those of Stanley Jevons. In his renowned book *Reflections on the Motive Power of Heat* (Carnot, 1897), Carnot emphasised the limited usefulness of measuring engine efficiency without considering other critical aspects such as safety, strength, durability, size or installation cost. Thus, if it is unwise to assess an engine's performance with a simple input/output indicator, it is even more precarious to do so with the energy performance of a complex system such as an entire country. On the other hand, Jevons pointed out the counterintuitive observation that increasing efficiency in resource use can lead to an overall increase in resource consumption instead of a decrease (Jevons, 1865). This phenomenon, known as the Jevons paradox or rebound effect, is associated with increased consumption due to the relative cost reduction of the resource resulting from the efficiency improvement (Sorrell, 2009). For instance, improved efficiency of light bulbs can lead individuals to use more because they consume less energy, or consumers may redirect efficiency savings toward another activity, thereby altering the system's dynamics and leading to heightened resource utilisation (Giampietro and Mayumi, 2018; Martinez-Alier, 1987).

From a metabolic perspective, the use of efficiency indicators to characterise whether there are improvements in the sustainability of a social-ecological system can be considered a fallacy (Velasco-Fernández et al., 2020). As we saw in Chapter 3, human systems are open dissipative systems that can maintain their identity (i.e., a determined state) because of a continuous metabolism process which requires stabilising a coordinated inflow of matter and energy resources (i.e., generating environmental pressures and impacts). Sustainability is about the stability of the relation between: (i) social sustainability, i.e. the ability to reproduce the flows and funds used in the economy; and (ii) ecological sustainability, i.e. the natural reproduction of ecological funds and their ability to both supply primary flows going into the society and to absorb wastes coming out of the society. Therefore, what is essential for achieving more sustainable state-pressure relations is to reduce the overall or absolute amounts of energy and materials (the primary flows coming from and getting into the environment), respecting biophysical limits concerning the use of natural resources, ecosystem assimilation and planetary boundaries. This sustainable state would be achieved through the definitions of absolute biophysical budgets, which would, in turn, require a process of social discussion within the scope of post-normal science, considering both local resource usage and externalised impacts rather than solely focusing on improving relative process performances or budgets that disregard crucial externalisation processes.

A characterisation of changes in the sustainability of metabolic systems can be obtained by combining extensive variables (assessing the size of fund and flow variables) and intensive variables determined by specific flow/fund ratios (e.g. the level consumption per unit of size), flow/flow ratios (input/outputs) or fund/fund ratios (relative sizes of different elements). For this reason, efficiency indicators obtained by calculating flow/flow ratios are irrelevant to sustainability analysis (Giampietro et al., 2012). For instance, consider the relation between total energy consumption in gross energy requirements (GER) and gross domestic product (GDP) using the Equation 3:

$$GER = \left(GER \cdot \frac{1}{€\ of\ GDP}\right) \cdot (€\ of\ GDP) \tag{3}$$

If a decrease in energy intensity (the first term of the equation) of 20% results in an increase of the GDP (the second term) of 40%, the overall value of GER will still go up, resulting in more environmental pressures despite the improvement in efficiency. It is important to note that the quantification of “efficiency” in conventional narratives is not only always based on intensive variables but also associated by default with the idea of “improvement” (Dunlop, 2022). However, this issue relates to a deeper discussion about societal goals. Efficiency gains can technically reduce resource consumption with equal output, but widespread normative convictions (dominant narratives) mean that output must be increased instead. Consequently, questioning the “default” assumption about the desirability of perpetual growth should be a must.

Two more issues arise when using an energy efficiency indicator. First, demographic variables are key factors determining the performance of a social-ecological system, a factor that the current economic indicators of efficiency missed. Population growth can compensate for an improvement in energy intensity associated with less consumption of energy per capita. Second, using monetary variables could be problematic from a biophysical perspective. Decoupling the dollar from gold marked the definitive disassociation between the processes of money creation and the physical world, as well as the complete dematerialisation of the financial universe (Naredo, 2019). Money is often created from nothing and extinguished into nothing during a recession, contrary to the dictates of the first law of thermodynamics (Mayumi and Renner, 2023).

In general, empirical evidence shows that approaches based exclusively on efficiency from technological improvement have proven insufficient to achieve significant reductions in energy demand (Calwell, 2010; Peñasco and Díaz-Anadón, 2023). This approach can also be counterproductive by legitimising increasingly energy-intensive lifestyles (Shove, 2018). In turn, increases in efficiency pave the way for new applications, as suggested by the Jevons paradox. This issue suggests that, despite technological advancements to reduce energy consumption, complex systems cannot be totally controlled, and systemic responses may offset the benefits of these improvements (Giampietro and Mayumi, 2018). For these reasons, existing policies aiming to increase efficiency must be complemented by the pursuit of sufficiency (Princen, 2005), that is, the direct downscaling of economic production in many sectors and a parallel reduction of consumption (O’Neill et al., 2018).

Figure 6.1 shows the evolution of energy intensity and the gross energy requirement (GER) in Andorra for 2012-2022. GER is reported in virtual Joules of thermal equivalent following the partial substitution method, i.e. how much thermal energy would be required to produce all energy carriers used in the country. This method avoids the misleading effects generated by the physical content method or the direct equivalent method (Giampietro et al., 2013). Although energy intensity drops by 30% throughout the observed timeframe, GER, a relevant sustainability indicator giving information on a particular dimension (i.e. energy) and a determined scale (i.e. the whole country), only registers a 10% decrease. Notably, while the energy intensity exhibits a relatively stable trend, GER proves to be more responsive to demographic changes. Hence, we can consider an explanation for the sudden decrease in energy demand in 2020. This decrease was caused by the drop in visitors and tourists due to the COVID-19 pandemic. Moving to another technical explanation, GER reduction has been mainly achieved through the wide-scale adoption of district heating and improvements in the isolation of new construction buildings, reducing fuel consumption as heat (Miquel et al., 2021).

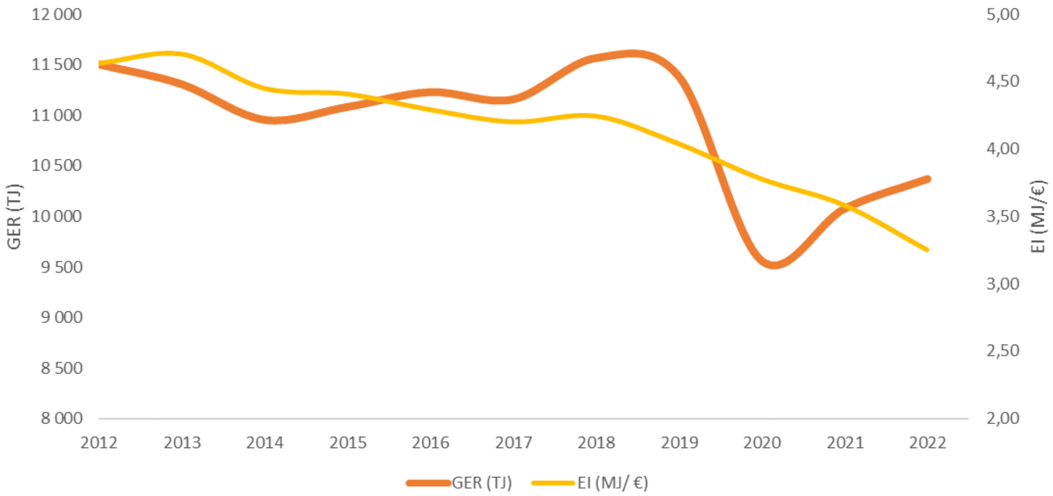

Figure 6.1. Gross Energy Requirements (GER) and energy intensity evolution for 2012-2022. Source: own elaboration from Department of Statistics (2023).

Considering the GER values for 2022 and the equivalent population of Andorra for that year, we obtain a consumption of 87 GJ per capita. This value is far from the 31 GJ per capita estimated for 2050, which is considered fair in a scenario of equitable redistribution between the global North and South (Keyßer and Lenzen, 2021). In this sense, adequate reductions in GER are extremely unlikely to happen shortly because: (i) wide-scale adoption of district heating and enhancements in the isolation of buildings are relatively easily obtained one-time efficiency improvements that cannot be repeated for further reductions; (ii) the existence of a declining marginal rate of improvements[21] (Seibert and Rees, 2021); (iii) the likely appearance of different types of Jevons paradox

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[21] For instance, combustion engines are subject to the Carnot efficiency limit, solar cells are at the Shockley-Queisser limit, and wind turbines are at the Berz limit.

or rebound effects where efficiency gains are reinvested in additional consumption of the same product —direct rebound effect— or resources freed by an efficiency improvement are re-allocated to another type consumption —indirect rebound effect (Parrique et al., 2019); and (iv) the majority the existing housing stock requires extensive maintenance and high exosomatic energy demands as we saw in Chapter 4. All of this suggests that independent of what happens concerning energy intensity indicators, there is a high uncertainty that future energy requirement reductions will be permanent and sufficient, especially in a context where increased population and economic growth are assumed by default.

6.3.2. The narrative of energy sovereignty based on renewables.

The massive deployment of renewable energy is a win-win solution in the conventional framework to meet sustainability goals. In this official story-telling, these technologies reduce dependence on fossil fuels, lowering greenhouse gas emissions while promoting local production and facilitating greater energy security. These knowledge claims are based on conventional economics' concept of "perfect substitutability" among resources. This idea sinks its roots in the seventeenth and eighteenth-century mechanistic philosophy that considered matter as universally malleable and manipulable and immune to qualitative change, and that served to separate the study of the economy from the physical world (Naredo, 2015). However, this belief is contested when adopting a metabolic perspective, where energy cannot be treated as a single entity because its various forms continuously transform into each other and possess irreconcilable qualitative distinctions (Giampietro and Bukkens, 2022).

As discussed in Chapter 3, the coupling of function and structure (i.e. the concept of holon) is essential for characterising elements of a complex system. The consideration of function, i.e. the existence of differences in output, implies that not all Joules produced by elements of an energy system are equivalent. In this regard, we can detect different functional categories producing various types of electricity (Renner and Giampietro, 2020):

- Power capacity producing base-load electricity. These elements generate electrical energy predictably, but their supply is difficult to regulate (e.g., a nuclear power plant).

- Power capacity producing peak-load electricity. These elements produce electrical energy predictability, and their supply is easy to regulate (e.g. a gas turbine power plant).
- Power capacity producing intermittent electricity. These elements make electrical energy non-predictable, and their supply cannot be regulated, only curtailed (e.g. wind turbines and photovoltaic panels).

Framing the issue in this way allows the detection of a systemic problem with the class of power capacity producing intermittent electricity concerning the ability to stabilise the distribution of electric power in the grid, matching supply and demand: it may produce electricity when it is not needed, and it may not have electricity when it is required (Renner and Giampietro, 2020). Therefore, without large-scale storage capacity, renewable technologies (e.g. wind farms and photovoltaic plants) do not have the same usefulness for running the grid as conventional technologies, many of them using fossil fuels (Smil, 2016a). Here lies the prevalent challenge associated with the large-scale integration of intermittent sources of electricity into existing grids. Due to insufficient storage capacity and inadequate demand adaptation, conventional sources are still needed to guarantee a fluent distribution of electricity in the grid. Without proper storage capacity, further investments in power capacity to harvest variable renewable energy sources (e.g. wind and sunlight) will fail to solve the energy system's decarbonisation problem (Smil, 2016a). Moreover, they may also worsen energy sovereignty by increasing costs and stressing the local grid. In short, an increase in installed capacity (having more GW of power) is not applaudable if it is not linked to equivalent stable growth in the amount of electricity produced and consumed in the grid (Renner and Giampietro, 2020). Unfortunately, a large-scale increase in storage capacity based on batteries is still a technical problem[22] (Seibert and Rees, 2021). It can further result in difficulties concerning the limited availability of critical materials (European Commission, 2020).

The problem with materials is more than just about storage devices. The material intensity of renewable energy is higher than that of fossil energy, comparing energy technologies based on their structure. Deploying “green technologies”, i.e. wind power,

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[22] The world's largest lithium-ion battery manufacturing facility, operated by Tesla in Nevada, can only store enough energy to meet the current US electricity demand for three minutes despite running at total capacity for a year. Furthermore, these batteries have a lifespan of only 5 to 15 years, which poses a significant challenge for waste management.

solar photovoltaic or solar thermal power, requires enormous amounts of raw materials, some with high supply risk (Valero et al., 2018). An electric power of 1 000 MW with 200 wind turbines of 5 MW currently needs about 160 000 tonnes of steel, 2 000 copper, 780 of aluminium, 110 of nickel, 85 of neodymium and 7 of dysprosium. Let us compare the materials needed to produce that same amount of energy using natural gas as fuel. We get about 25 times fewer metals: 5 500 tonnes of steel, 750 tonnes of copper, and 750 tonnes of aluminium (Almazán et al., 2021). In the case of photovoltaics, the problem is similar. New models that have achieved higher efficiencies than silicon require copper and silver, indium, gallium and selenium, or tellurium and cadmium, in addition to copper and silver, depending on the technology used (Valero et al., 2021). It should be remembered that when we talk about an energy system based on renewable flows, the only thing renewable is the flow of solar radiation that reaches the Earth. The rest, wind generators, photovoltaic panels, or transmission lines, are not renewable. These artefacts are an extension of fossil fuel energy since they require several oil-derived products, heavy machinery for mining resources, concrete for construction, and additional heavy machinery for installation, maintenance and decommissioning (Smil, 2016b). In this regard, an energy transition based on the massive deployment of renewables involves moving from a society dependent on fossil fuels to one highly dependent on minerals (as well as on fossil fuels). This point exemplifies problem shifting where efforts to solve an environmental issue (e.g. GHG emissions) can create new ones or exacerbate others (e.g. land use, metal extraction and waste management conflicts).

Finally, from a systemic perspective considering parts/whole relations, it is essential to note that a massive deployment of renewables will need to reorient the economy towards smaller size and complexity. Fossil fuels are highly concentrated energy sources with a high energy density, which means that with little mass and volume, they provide much energy (Smil, 2015). In addition, this facilitates a high rate of energy return on investment (EROI), that is, a good ratio between the energy they provide and the energy invested in obtaining them. On the contrary, the properties of renewable energies, which ultimately take advantage of the sun's energy, are antagonistic to those of fossils. Solar energy is very dispersed on the Earth's surface, implying a low EROI since a considerable amount of energy must be invested in concentrating solar radiation in its various forms (González-Reyes, 2022; Smil, 2015). In metabolic words, a social-ecological system based on renewable technologies needs greater allocation of end-uses and primary sources in its energy sector. These high requirements involve a lower strength of the hypercycle part, which determines a lower level of differentiation of the activities that can be afforded in the dissipative part (i.e. the share of service, government, and household sectors in the economy) (Giampietro et al., 2012).

Figure 6.2 helps us understand the situation in Andorra for 2012-2022. The figure shows the high growth of the installed power capacity in photovoltaic energy, the leading green technology awaiting the take-off of wind power in the country, from around 20 kW in 2012 to more than 1 880 kW in 2022. Although there is still much scope for implementing this technology with numerous projects under development, the fact is that for the period considered, the country's total electricity demand and the import of electricity from neighbouring countries show similar behaviour. Total demand has fallen 5% while imports have fallen 9%.

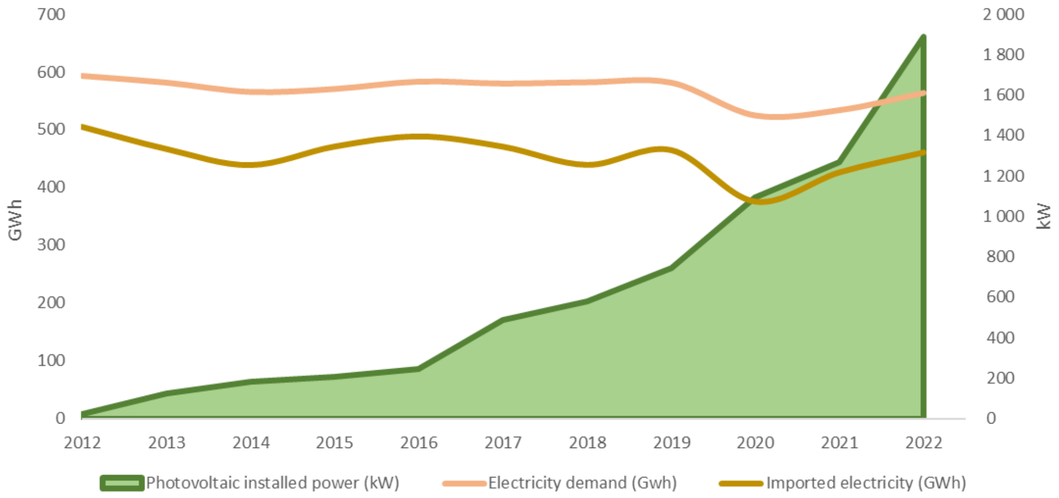

Figure 6.2. Photovoltaic power capacity (values on the right), electricity demand and imported electricity (values on the left) for 2012-2022 in Andorra. Source: own elaboration from FEDA (2022, 2021, 2020, 2019).

Still, this fact seems more related to increased electricity production from the only waste power plant in the country —its production has gone from 2% of total demand in 2012 to 3% in 2022— and the implementation of different cogeneration plants —which in 2022 cover about 1% of total electricity demand. Photovoltaic energy accounts for less than 1% of the total electricity demand in 2022 (FEDA, 2022). In this sense, for the moment, the important increase of power capacity in renewables has had little effect on the country's energy sovereignty. On the other hand, if we consider the values for the year 2022 of total demand for electricity and hydroelectric production as fixed and assume a constant increase in photovoltaic output of 25% per year —which is the increase that occurred between 2021 and 2022— (FEDA, 2022), in 21 years, that is to say by 2043, the objective established concerning the rise of the national electricity production proposed in the sustainability policies of the country would be achieved. It remains to be seen how intermittent and storage problems would be solved under this restrictive and simplistic scenario.

Finally, an analysis of the expected functions improves the quality of the debate on the possibility of increasing energy sovereignty. While hydropower serves as the principal technology in the local energy sector of Andorra, supplying peak electricity during high imported electricity prices (FEDA, 2019), critical functions in the country, such as refrigeration in large commercial areas and ski-slope infrastructure, rely on imported baseload electricity. However, only 19% of the final energy is in the form of electricity (BOPA, 2018). The other 81% is imported liquid fuels covering all functions related to thermal energy (heat and fuels), such as road transport and heating services, which present formidable obstacles to their total electrification, especially from renewable sources (Seibert and Rees, 2021).

The role of science is not only to produce facts but also to communicate uncertainty. Andorra's transition to renewables faces different sustainability constraints associated with significant uncertainty. The viability and desirability of this transition are in doubt. Will there be enough economic resources to replace fossil fuels? Will society accept the radical change in social practices associated with living in a smaller economy? The transition is also under feasibility constraints. Will enough land be available to build the required energy infrastructure? Will the country be able to compete with other powerful countries to obtain the necessary minerals for renewable energy?

6.3.3. The narrative of electric cars.

Electric vehicles (EVs) are dominant policy solutions in the sustainable development domain. A transition to EVs is justified by the promises of reduced GHG emissions, oil imports, and positive impacts on citizens through reduced pollution (Di Felice et al., 2021b). Moreover, the massive implementation of EVs allows the societal function of transport to be satisfied by the continued performance of a particular mobility practice associated with using private vehicles. Under the prevailing framework, the automobile, in its electric version, remains a central pillar of consumerism culture, embodying ideals of freedom, identity, autonomy, and individualism (Gartman, 2004).

EVs are a classic example of innovation as a central instrument of sustainability policy (Di Felice et al., 2021a). However, the solution that supposedly brings with them—decarbonising the private transport sector— creates new problems across other nexus dimensions. It is estimated that according to the expected trends, by 2040, more than half of the demand for critical minerals will come from the manufacturing of EVs, which rely on materials like lithium, cobalt, tellurium, and rare-earth metals (IEA, 2021). Each vehicle needs more than 200 kilograms of these minerals compared to just over 30 kilograms of a conventional car. Due to its scarcity, the complete replacement of internal combustion engine vehicles, along with a massive deployment of renewable energy that also depends on scarce elements in the earth's crust, collides with the biophysical limits of the planet and seems implausible (Valero et al., 2021). This fact causes some authors to suggest implementing a degrowth scenario to make the material requirements for transitioning to global electrical mobility feasible (Pulido-Sánchez et al., 2021). Sustainability problems do not only appear on the input side. On the output side, i.e. wastes, only 5% of lithium batteries released on the EU market are recycled. The high cost of the process and the lack of standardisation complicate the recycling of these devices on a large scale (Gálvez-Martos et al., 2018). However, progress has been made in this direction (Aguilar-Lopez et al., 2024) and in using EV batteries as providers of short-term grid services (Xu et al., 2023).

The need for finite and critical materials entails socio-environmental impacts and conflicts at extraction sites (Velasco-Fernández and Pérez, 2022). Globally, almost 60% of cobalt production occurs in the Democratic Republic of Congo (INSIDEEVs, 2019), where mining activities are notoriously tied to child labour (Banza Lubaba Nkulu et al., 2018). Lithium reserves are mainly found in a handful of countries. In 2017, Australia, Chile, and Argentina were responsible for producing more than 90% of the raw material (INSIDEEVs, 2019). Lithium is becoming increasingly crucial for EV batteries, grid-level storage, and consumer electronics (Heredia et al., 2020). It is even called "the new gold" due to its geopolitical significance (Tarascon, 2010). Socio-environmental impacts of lithium extraction are under-studies and severe (Agusdinata et al., 2018). In general, extraction processes are linked to local environmental impacts such as the intensive use of water and waste generation (Flexer et al., 2018). The explanation narrative that frames EVs as a necessary solution in sustainability policy may be instrumental in minimising the voices of the communities affected by extraction processes. These processes, associated with generating environmental impacts and social conflicts, are expected to become more pronounced as the production of EVs increases and will probably result in new neocolonial policies in the global South (Hickel et al., 2022a).

A nexus biophysical reading detecting systemic problems concerning the massive introduction of EVs also needs an approach from biosemiotics[23] (Giampietro and Renner, 2020) to understand why electric vehicles are considered vital solutions in the policy domain. The EVs knowledge base is still being determined (Di Felice et al., 2021b). For example, there needs to be more knowledge about how many GHG emissions are associated with each step of the EV production processes or if a massive implementation will lead to substantial decreases in GHG[24]. However, innovations are central elements of the technological dynamism of capitalism (Harvey, 2010). In the dominant narrative, citizens become consumers, rational agents, and utility maximisers, and technology is seen as an unquestionable good. All these aspects are tied to the EV, where consumers will make "the right choice" if they have enough information (e.g., cars are eco-labelled to inform customers about their environmental impacts). Once issues are framed this way, technical and technological solutions become the "natural" pathway, strengthening and locking in a particular techno-optimistic imaginary. What do we think of when we talk about sustainable mobility? The answer is straightforward: the EVs. In this simplification process, healthier mobility alternatives (e.g. the bicycle), more inclusive (e.g. public transport), less individualistic (e.g. shared cars), or less powerful (e.g. smaller and lighter cars) options are displaced from the debate on a sustainable mobility model. In this context, EVs have become a political tool to reconcile the tension between conflicting policy objectives, where economic growth is continuously coupled with environmental protection. Therefore, EVs become an instrument for governments to pursue their leadership for sustainable growth while depoliticising the material requirements, inequalities and other socioenvironmental impacts of such growth (Levidow, 2013).

Figure 6.3 shows the evolution in Andorra's electric vehicle fleet compared to the total fleet of vehicles for the period 2012-2022. As can be seen, the fleet of electric

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[23] As explained in Chapter 3, and mentioned in the introduction, biosemiotics is the scientific discipline that deals with the ability of living systems to interpret the signs arriving from their context so as to check the quality of the process guiding their actions. Biosemiotics shows that concepts like purposes, beliefs, and an operational definition of what should be considered the "truth" are basic components of the decision-making process of all living systems.

[24] Consider the environmental implications that a complete replacement of internal combustion engine vehicles by EVs would mean in terms of increasing the installed power of electrical production, enhancing the capacity of high voltage lines, and replacing petrol stations with recharging points.

vehicles has experienced accelerated growth, especially since 2015. The total number of EVs (approximately 750 vehicles in 2022) corresponds to 1% of the entire fleet (about 95 000 vehicles in 2022). This figure is far from the expected percentage of 20% by 2030. However, assuming a constant vehicle fleet of about 95 000 units and a sustained annual growth rate of 30% from 2022 (value of the increase in 2022 over 2021) would reach 50% of the fleet in electric vehicles by 2038. In general, the particular relation of a dissipative system with its context is a critical factor in explaining the success or failure of a determined policy solution. In the specific case of Andorra, its geographical location plays an essential role in the current lack of acceptance of EVs. Apart from a little airport in the nearby town of La Seu d'Urgell, road networks are the only means of access to neighbouring countries and the sea. This is why private car transport is widespread in Andorra, involving high levels of exosomatic energy consumption in the household sector (see Chapter 4). EVs' lack of autonomy and lousy performance in a cold environment seem to be determining factors in users' choice of internal combustion engine vehicles. Improvements in the performance of EVs, the evolution of fuel prices and the establishment of rigorous emission measures for private cars may lead to greater use of electric vehicles than, in any case, is shrouded in great uncertainty.

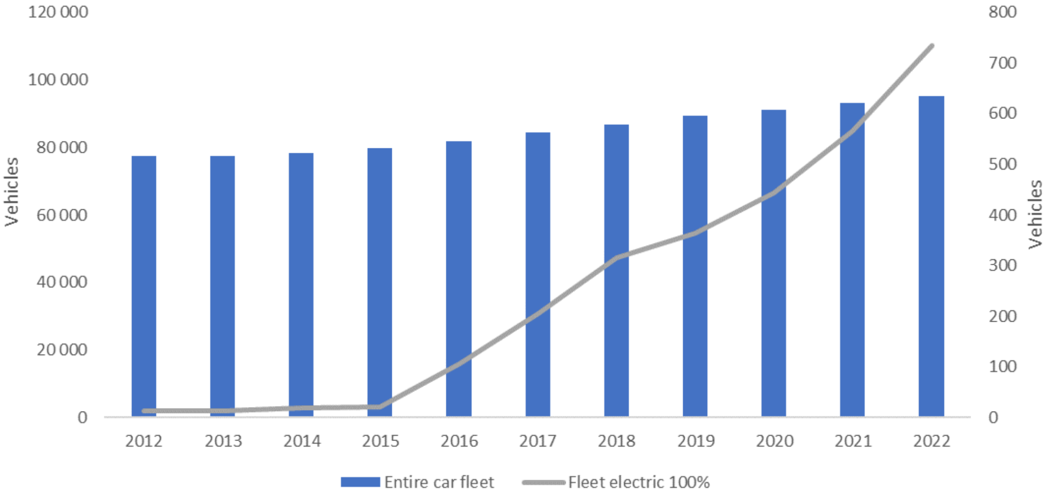


Figure 6.3. Entire car fleet (values on the right) and evolution of electric car fleet (values on the left) in Andorra for 2012-2022. Source: own elaboration from Department of Statistics (2023).

6.3.4. The narrative of the circular economy.

The unprecedented success of the term circular economy lies in the high expectations it raises about environmental, social and economic benefits where the traditional linear process of production and consumption would be turned into a "closed-loop" (Escrivà, 2022). According to the Ellen MacArthur Foundation (EMF, 2024), “the circular economy is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources.” This foundation, which has Nestlé, Visa, and Gucci among its strategic partners, had the honour of boosting the circular economy concept, which gained popularity after the presentation of the EU Plan for the Circular Economy (European Commission, 2015). In the case of Andorra, establishing a circular economy is a fundamental pillar in waste management (BOPA, 2018). Of course, closing the loop between waste and extraction via recycling is a sensible goal, and in theory, one would want any economy to be as circular as possible. However, it is important to remark on the existence of limits to this circularity and the contradictions it posts by projecting an imaginary scenario where sustainability is achieved solely through performance improvements in production processes.

The boom of the circular economy can be contextualised within the debate about the sustainability of industrial societies that took place in the 70s. The discussion was fought between the “cornucopians, whose leading voices were Robert Solow and Julian Simon, and the “prophets of doom”, among whom Nicolas Georgescu-Roegen, Paul Elrich and Howard T. Odum (Giampietro et al., 2012). The first endorsed the ideology of conventional economics (see Chapter 2), maintaining that technology, human ingenuity and the market would always overcome any biophysical constraint to continuous economic growth. The second, on the other hand, framed the issue of sustainability based on biophysical and ecological analyses, claiming that natural resources and the fragility of ecological processes would sooner or later impose limits to perpetual economic growth (Giampietro, 2019; Giampietro et al., 2012). The complex systematic environmental crisis (Richardson et al., 2023), or global polycrisis (Lawrence et al., 2024), has questioned the apparent uncontested success of the “cornucopians”. In this context, the surging of the circular economy is only the last ideological resource to perpetuate the illusion that it is possible to respect biophysical limits (i.e. achieve a sustainable state-pressure relation) while maintaining or even reactivating economic growth (i.e. keeping the current level of social desirability) (Bonaiuti, 2022). The overall strategy is to progressively close the recycling cycles of the economy’s materials, thus maintaining growth and sustaining employment. However, this process is subject to substantial limits and, in any case, will not reactivate but will slow economic growth (Giampietro, 2019).

From a metabolic perspective, the economy is embedded in physical realities. The economic process is not circular but entropic (see Chapters 2 and 3). Any activity related to fulfilling a socially relevant function, such as moving, warming, or refrigerating, produces the irreversible degradation of a certain amount of energy that can no longer be used at the end of the process. The law of entropy tells us that the recycling of energy is a vain proposal and that there is a practical limit to the recycling of materials (Arenas et al., 2022). In this regard, a distinction must be made over different types of flows that should be considered when dealing with the circularity of the economy (Figure 6.4):

- Primary flows enter from the ecosphere into the anthroposphere (e.g. tonnes of coal, oil, or cubic meters of water). These flows are extracted from primary sources, such as coal mines, oil and gas fields or aquifers. Also, primary flows exit from the anthroposphere to the ecosphere (e.g. waste, pollutants), requiring the regeneration capacity of primary sinks (e.g. the atmosphere or water table).
- Secondary flows derived from the exploitation of primary flows. For example, in energy statistics, secondary energy is represented by energy carriers, such as electricity or gasoline, produced from primary energy sources (e.g., wind and fossil energy). Note that secondary flows are, at the same time, inputs and outputs produced and consumed within the anthroposphere.
- Tertiary flows are derived from recycling secondary flows (e.g., paper recycled from waste paper, which is a secondary flow).

The definition of the circular economy refers only to the “products, components and materials”, i.e. secondary and tertiary flows under human control inside the anthroposphere that are used to express functional tasks associated with the concept of end-uses (see Chapter 3). However, the entropic narrative dictates that the production of secondary and tertiary flows requires the availability of corresponding primary flows depending on processes outside human control in the ecosphere. Therefore, the idea of circularity of flows without using any service from the ecosphere is impossible. For example, the biogas from the manure or the electricity produced by burning solid urban waste are both tertiary flows obtained from recycling wastes generated by the previous use of secondary flows. While the input from tertiary flows is undoubtedly a welcome contribution to more effective use of resources, their very existence depends on the previous use of secondary flows, which depends on the prior availability of primary flows. In the case of biogas, primary flows (e.g., green and blue water and fertile soil) were used to produce the animal feed, which was converted into manure for producing biogas. In the case of electricity produced from waste, primary flows (e.g. oil, gas) were used to convert the discarded products that ended up in solid waste into electricity.

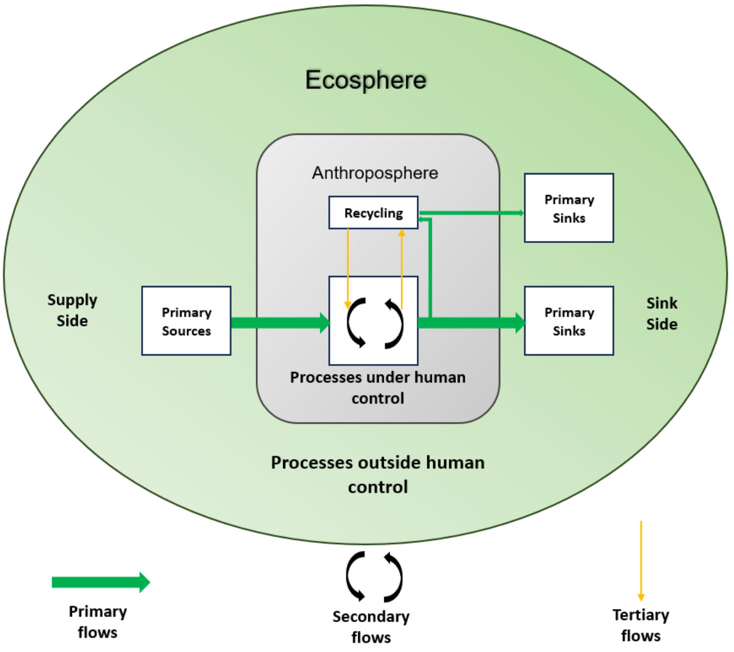


Figure 6.4. Different typologies of flows inside the metabolic pattern of a human society connecting the Ecosphere and the Anthroposphere. Adapted from Giampietro (2019).

In practical terms, considering a metabolic perspective tells us that only a tiny portion of the materials and energy needed for the metabolism of industrial societies can be recycled. Some believe that the percentage of materials that are either reused or recycled is as low as 6% at the global level (Haas et al., 2015). Recycling can be done, but only to a certain extent and at a specific cost, and only if the corresponding primary sources are available. This limitation is because:

1. A significant proportion of our products cannot be recycled. Still, they dissipate following the fundamental laws of thermodynamics (e.g. energy, food), depend on natural processes beyond human control (e.g. water cycled) or belong to the stock of built environment (e.g. construction materials) (MAGIC Consortium, 2020).
2. Recycling itself necessitates energy. Suppose the energy required to transform a material disposed of is higher than the energy needed to obtain a raw material.

In that case, whether recycling is a desirable solution must be questioned. Moreover, most of the time, new materials are needed in the recycling process, which would also need to be recycled at some point, requiring additional new material, and this ad infinitum (Parrique et al., 2019).

3. Many modern products are too complex to be recycled, and when this is technically feasible, it is often costly and thus less economically attractive. Reuter et al. (2018) studied the recyclability of one of the most popular smartphones and found that the best possible recycling scenario would only recover about 30% of the materials. As stated in the previous subsection, most problematically, it is the case for technology to harvest and store renewable energy. UNEP (2011) estimates that less than 1% of speciality metals are recycled.
4. In a growing society, the ability to recycle is slower than the will to produce. Therefore, as the fraction of materials that can be recycled will always be smaller than the material needed for growth, virgin resources will have to be used (Parrique et al., 2019).
5. The internalisation of recycling flows, i.e. the changes required to make the economy more circular, increases the cost for the economy and reduces its performance. Production factors must be invested in generating services (i.e. the recycling of flows) that would otherwise have been provided free by nature, incurring an opportunity cost (Giampietro, 2019). In particular, repairing, reusing, and recycling are human-intensive activities, which, in enriched societies, become one of the costliest production factors (Manfroni et al., 2021). As reusing and repairing require local labour, buying new products is usually cheaper than fixing them. In this context, it is expected that informal immigrant waste pickers will be engaged in recycling and exporting waste to countries with lower labour and environmental protection (Eurostat, 2024).

Table 6.2 provides some reflections on circularity in Andorra for the year 2019. Official documents indicate a recycling rate of 23% (upper part of Table 13) due to recycling paper, cardboard, scrap metal, wood, and glass (Andorran Government, 2020). Within the borders of Andorra, only material is collected and selected, and the recycling process takes place in neighbouring countries, releasing the country from the economic costs of such recycling. However, this accounting considers only material that ends up as waste. If we also count the materials necessary for the maintenance of endosomatic metabolism (food) and exosomatic (energy carriers) of Andorra and that dissipate during the process (intermediate part of the table), the recycling rate drops to 10% (bottom part of the table). Whatever the accounting consideration, the metabolism of Andorra is based, as evidenced in Chapters 4 and 5, on non-renewable stock exploitation of fossil energy (stock-flow) supply and the unsustainable filling of sinks (e.g. GHG in the atmosphere). This results from increasing productivity through linearising the economy, primarily achieved by the intensive transformation of fossil fuels and raw materials into waste and emissions.

Table 6.2. Different types of materials in the societal metabolism of Andorra for the year 2019.

Type of material	***Tonnes***	***Percentage***
Materials intended for disposal in controlled landfills	2 565	2%
Recycled and reutilised materials	31 548	23%
Waste-to-energy	40 855	30%
Another recovery	60 401	45%
Total waste	*135 369*	*100%*
Direct imported vegetables	30 163	
Direct imported meat	5 403	
Total endosomatic metabolism	*35 566*	
Petrol	22 509	
Diesel	84 638	
Domestic fuel	43 388	
Total exosomatic metabolism	*150 535*	
Recycled and reutilised materials considering societal metabolism requirements		10%

Source: Andorran Government (2020) *for the different types of waste.* Miquel et al. (2021) *for the tonnes of gasoline, diesel and domestic fuel using a calorific value of 10 700 kcal/kg for petrol and 10 350 kcal/kg for diesel and domestic fuel.* Agricultural Department (2019) *for directed imported vegetables and direct imported meat.*

6.3.5. The untold narrative of externalisation.

Most statistics, analyses and policies in the sustainable development domain take a territorial “production-based approach” perspective. Accordingly, environmental pressures are assigned to the country (or region or city) in which they are generated. For instance, official GHG emissions inventories use a territorial approach for commitments, negotiations and declarations of intent under the United Nations Framework Convention on Climate Change (UNFCCC), as exemplified in Andorra in Miquel et al. (2021). However, the global economy is characterised by massive flows of goods traded between different territories. Therefore, it is also essential to consider the environmental pressures caused by domestic demand regardless of where they occur. This viewpoint is known as the “consumption-based” perspective (Roca-Jusmet and Padilla-Rosa, 2021).

From a metabolic framework, a consumption-based perspective is related to the lack of metabolic security, i.e. when local consumption exceeds local production (Giampietro et al., 2020). An essential aspect of the metabolic pattern concerning metabolic security is the distinction between the anabolic and catabolic compartments inside the anthroposphere. On the one hand, the catabolic part of the metabolic process comprises the processes in the economy’s primary production sectors (i.e. agriculture, energy, and mining). This part is called catabolic because, in analogy with biochemical processes, primary sources (e.g. oil, gas, green water) are degraded to produce secondary inputs (petrol, liquefied natural gas, food) for use inside the anthroposphere. On the other hand, the anabolic part of the metabolic process occurs in the economy’s remaining sectors (i.e. household sector, manufacturing and construction, and service and government). This part is called anabolic because, like in biochemical processes, secondary (and tertiary when recycling) are used to generate products and materials needed to build and maintain the activity of society and reproduce its structures. A high fraction of the required end-uses and environmental pressures associated with the operations of the catabolic compartment limits the ability of the metabolic system to express a diversity of functions and structures in the anabolic compartment, which is tied to the consumption of goods and services in the economy. In this way, importing provides a degree of freedom to the congruence of this set of relations (Giampietro, 2019).

As analysed in Chapter 5, Andorra is a classic example of a dissipative system that must be open. The performance of its endosomatic and exosomatic metabolism relies on the massive externalisation of production processes belonging to its catabolic compartment, i.e. the agriculture and energy sectors. Therefore, Andorra can specialise in service sector activities and be a tourist destination only because it externalises massive amounts of labour, land use, water, and emissions, displacing socio-environmental pressures on other economies. The point to be made here is that Andorra also relies on externalisation practices in the catabolic (mining and energy) and anabolic (manufacturing) compartments to achieve the goals of its local sustainability policies.

Thus, the country tries to ensure a pattern of sustainable development by externalising unsustainable practices elsewhere. This practice is evident with the environmental pressures and impacts associated with the materials and energy requirements needed for the massive implementation of green technologies in its energy sector or the use of electric vehicles in its transport sector. Alternatively, with the end uses and environmental pressures of externalised recycling processes to improve its economy's circularity. Besides, due to its deep structural coupling with neighbouring countries, the decarbonisation of Andorra's economy, promoted by its environmental policies, can only be achieved in combination with the decarbonisation of these countries. In this sense, Andorra behaves as an autopoietic system, continuously shaping and being shaped by other systems. For example, fuel imports sold as fuel tourism cannot be overlooked, as they account for a significant portion of total petrol and diesel imports —20% and 51%, respectively, as per Travesset-Baro (2017). Unless transportation from neighbouring countries is carbon-neutral, making fuel tourism irrelevant, emissions from fuel imports will remain an essential source of environmental pressure within the country. Similarly, decarbonisation in the energy sector of neighbouring countries is necessary to become carbon neutral in 2050 since imports will cover 50% of the electricity demand (BOPA, 2018). It remains to be seen how industrial processes such as plastic, cement, steel, glass or ammonia production, heavily dependent on petrochemical feedstocks and fuels, will be decarbonised (Smil, 2008).

One could argue that global dynamics of externalisation are beyond the reach of national sustainability policies, especially in a little country like Andorra. However, environmental challenges have a global dimension, and consequently, the effects of planning for sustainability should be evaluated worldwide (Angelo and Wachsmuth, 2015; Holgersen and Malm, 2015). Consider Angelo and Wachsmuth's (2015) critique of "methodological citysim": suppose a city (and Andorra can be considered a particular city) is inserted in a global system of exchange and is not analysable outside this system. In that case, its sustainability policies must also be evaluated in this context. This premise is compatible with Harvey's formulations about unequal geographical development and the impossibility of understanding what happens in a place without considering the spatial relations that sustain that place (Harvey, 2019). Furthermore, while sustainability focuses on local solutions in Andorra's planning documents, strategies extend beyond national boundaries for other, apparently more critical policy areas, like international competitiveness or fiscal policies (Andorra Business, 2023). This reflection underscores the importance of considering the country as part of and responsible for a network of relationships with its global hinterlands.

6.3.6. The narrative of growthism.

Economic growth is usually defined as an increase in the goods and services produced by an economy in a given period, typically a year. The essence of economic growth, as commonly understood, is a country's increase in Gross Domestic Product (GDP). According to Daly (2019), the present system of world growthism, in the broadly capitalist mode, is triumphant. Economic growth is seen as positive and necessary, a win-win solution to all problems. In the conventional narrative, growth remains a central goal in sustainable development policies at all scales (Krähmer, 2020). Andorra's sustainability plans are aimed at achieving a balance between economic growth and environmental protection. As part of this effort, the country has projected a steady annual growth rate of 1.3% until 2050. Such a growth rate would result in a remarkable increase in GDP of more than 150% between 1990 and 2050 (Miquel et al., 2021).

Obsession with growth can be seen as the result of a particular semiotic process. Civilisations are shaped by their priorities in deciding what things and relations are valuable. For capitalism, the choice was clear and peculiar: "Value" is determined by labour productivity in commodity production (Moore, 2015). The exploitation of labour power is central to capital accumulation. The capitalists' quest for survival in competitive markets underpins the necessity of "accumulation through expanded reproduction". Capital must continually accumulate, and at the core of capitalism lies the constant pursuit of value production on an expanded scale. As a result of accumulation, growth (i.e. GDP increases) indicates the overall increase in the production of goods and services at the aggregate level (Andreucci and McDonough, 2015).

GDP is linked to income, and income is strongly correlated with consumption. From a metabolic perspective, a significant proportionality between consumption and impact exists for an extensive range of environmental, resource and social indicators (Wiedmann et al., 2020). The flow-fund model helps analyse the tension between economic growth and ecological sustainability. We now live in a full world because of exponential economic growth that boosted population and consumption per capita (Daly, 2005). This situation has implied an enlargement of the components of social systems and an increase in their complexity (Tainter, 2006): growing populations of humans, livestock, and artefacts such as cars or refrigerators, allowing greater technical abilities, hierarchy, differentiation, and specialisation in social roles. All these populations are fund elements, “dissipative structures” generating pressures and impacts, whose maintenance and reproduction require a metabolic flow based on throughputs. This throughput begins with the depletion of natural resources from the ecosphere and concludes with the release of polluting waste back into the ecosphere. The validity of the green growth discourse relies on the assumption of an absolute, permanent, global, significant, and fast decoupling of economic growth from all critical environmental pressures to avoid passing irreversible thresholds of damage, such as the nine planetary boundaries identified by Rockström et al. (2009), Steffen et al. (2018) and Richardson et al. (2023). However, no empirical evidence exists for such a decoupling (Parrique et al., 2019). The question becomes how much reduction in consumption and production can be socially sustainable, safeguarding human needs and well-being (Hickel et al., 2022b).

The detrimental effects of economic growth on the possibility of achieving a significant reduction of environmental pressures can be observed through an analysis of the case of Andorra. Climate change provides an excellent example of a hard deadline for absolute emissions reduction. According to the sixth IPCC report (IPCC, 2021), to continue with the current path of GHG emissions, an increase between 2.8 and 4.6 degrees is estimated to be highly probable by 2100. It is unlikely that human civilisation, in its current globalised and hyper-consumer configuration, can sustain such increases. What is certain is that most crops and agricultural systems on which our food depends will not withstand the rise (Gowdy, 2020). For this reason, well-documented studies consider that the rate of reduction of emissions would be 6% per year for four decades, starting in 2013 (Hansen et al., 2013). Likewise, the EU Energy Road Map (European Commission, 2012) aims to reduce emissions to 80% below 1990 levels by 2050. However, the emissions policy in Andorra is based on lowering non-absorbed emissions (by 37%) compared to a hypothetical BAU scenario linked to constant economic and population growth (BOPA, 2018). Figure 6.5 shows the path of non-absorbed emissions and the reduction target by 2030. From a hypothetical scenario that assumes growth, the commitment to reduce is modest. Expected emissions by 2030 are 334 Gg CO2eq, 34% higher than in 1990. This result would leave an estimated 4.8 tCO2eq emissions per capita in 2030, far from the 1.1 tCO2eq per person per year between 2021 and 2050 (and zero afterwards), to stay below 1.5ºC global temperature increase (Chancel et al., 2022). This outcome would also significantly complicate carbon neutrality targets by 2050.

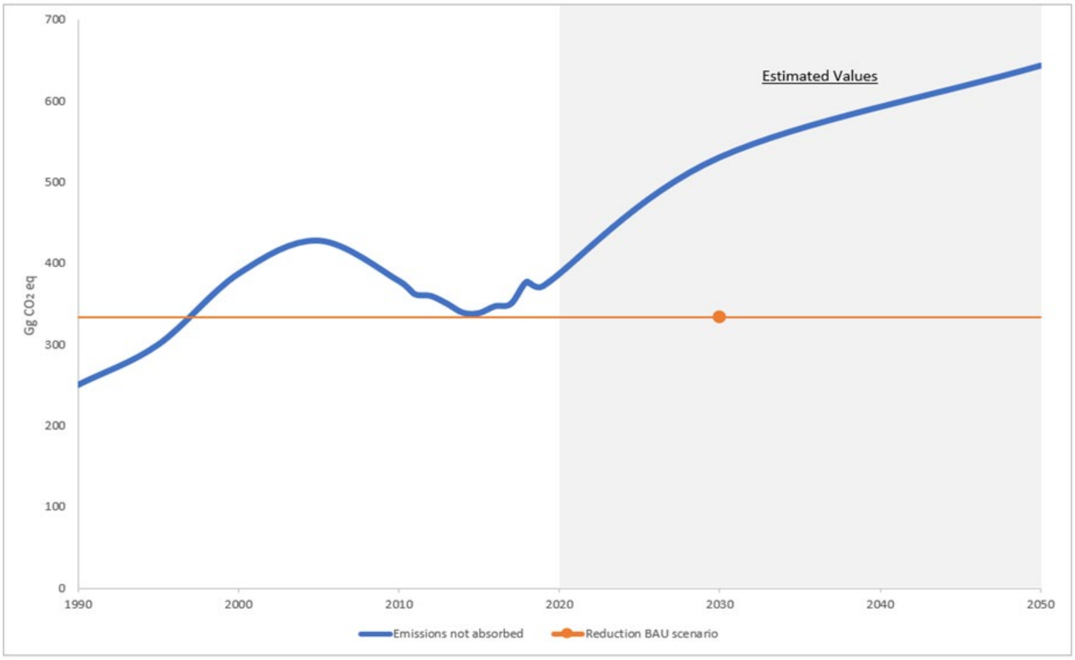


Figure 6.5. Emissions not absorbed and estimated reduction according to a Business as Usual (BAU) scenario. Values until 2019 are actual and estimated from 2020. Source: elaboration from Miquel et al. (2021) and BOPA (2018).

Beyond one-dimensional visions related to emissions, it is essential to remember that Andorra needs materials, energy, and proper handling of the wastes it generates to maintain its current size. The maintenance of one hour of human activity or one square meter of land use is associated with a particular economic and biophysical performance, as shown in Chapter 4, and it translates into an expected pattern of state-pressure relations. A growing economy would only increase these requirements, exacerbating environmental pressures and impacts exerted on local, regional and planetary levels. This predicament entails that sustainability concerns must be associated with the existence of biophysical limits that make perpetual economic growth unfeasible.

6.4. Conclusion.

Today, national states are charged with facilitating society's socio-ecological transformation (Geels, 2011; Koehler et al., 2017). Because of the legitimation imperative of the national state, intimately tied to the normalisation of consumerism, material abundance and well-being, there is an invisible yet effective structural barrier to environmental sustainability that Hausknost (2020) calls "the glass ceiling of transformation". In this context, the only available strategy to reduce the systemic unsustainability of society's metabolism under the dominant narrative is to "decouple" economic growth from environmental impact by reducing resource use (e.g. the circular economy) or increasing energy efficiency. In turn, the decarbonisation of the economy is based on the massive deployment of green technologies (e.g. electric cars and renewable technologies), generating expectations within socio-technical imaginaries (Jasanoff and Kim, 2015), with soothing effects that push political aspects out of the sustainability discussion in what Swyngedouw names “the post-political condition” (Swyngedouw, 2010).

The need for legitimacy calls for endorsing simplistic scenarios based on implementing policy legends (Giampietro and Funtowicz, 2020), in which solving all the problems is possible simultaneously. Thus, the current use of economic narratives under the conventional framework allows for a kind of painless framing where the existence of trade-offs between different policy solutions (e.g. solving the problem of how to reduce the use of fossil fuels may aggravate how to sustain economic growth) and tensions between different nexus dimensions (e.g. “green” technologies can exasperate environmental impacts in extraction sites) are suppressed from the policy discussion. The sustainability predicament is presented as a problem of finding and applying the right technology and correcting individual consumer behaviour. This is, in fact, a relatively comfortable situation for businesses and policymakers. All responsibility for sustainable development is externalised to experts to provide and decide upon the best technologies or strategies and consumers to make the right choices in the marketplace (Hobson, 2002). However, this position has been criticised as overestimating the capacity of experts to determine the “right decisions” (Funtowicz and Ravetz, 1993) and for not considering that social practices are reflections of prevailing social and economic structures and not of consumers’ preferences (Haberl et al., 2021).

Based on the QST approach, this chapter has explored the existence of an alternative story using a metabolic framework about given policy issues that can help to check the quality of the original framing and enrich the diversity of insights. The main objective was to bring to light alternative knowledge claims that can improve the quality of the debate in the sustainable development domain in Andorra. Table 6.3 summarises the main findings.

Table 6.3. Discussion of relevant issues in the sustainable development domain using the conventional and metabolic frameworks.

Relevant issues in the sustainable development domain	***Conventional Framework***	***Alternative framework based on a metabolic approach***	***Findings for Andorra***
Efficiency	Increases in "efficiency" are practical solutions to reducing resource consumption and related emissions. Efficiency indicators are helpful indicators for determining whether there have been sustainability improvements.	Reducing the overall or absolute amounts of energy and materials is essential for sustainability. Therefore, efficiency in policies falls short of respecting biophysical limits. A biophysical characterisation must combine extensive variables (assessing the size of fund and flow variables) and intensive variables (determined by flow/fund ratios, among others). Efficiency indicators are irrelevant to sustainability analysis.	While energy intensity (EI) has fallen by 30% from 2012 to 2022, gross energy requirements (GER) have only decreased by 10%.
Massive take-up of renewable energy	Renewable technology is a win-win solution, reducing dependence on fossil fuels and increasing energy sovereignty.	Without large-scale storage capacity, renewable technologies (e.g., wind farms and photovoltaic plants) are not as helpful in running the grid as conventional technologies. Moreover, "green technologies" are more material-intensive than traditional technologies.	The radical increase of power capacity in renewables has had little effect on the country's energy sovereignty.
Electric vehicles	A transition to electric vehicles is justified by the promises of reduced GHG emissions, oil imports, and positive impacts on citizens through reduced pollution.	Electric vehicles are a classic example of innovations as central instruments in sustainability policy linked to different problems and significant doses of uncertainty from a nexus biophysical reading. They are also used as artefacts to reconcile conflicting policy objectives.	EV penetration only accounts for 1% of the total fleet of vehicles.
The circular economy	This term raises high expectations about environmental, social, and economic benefits. In a circular economy, the traditional linear production and consumption process would be turned into a "closed loop."	The economy is embedded in physical realities. The economic process is not circular but entropic. Consequently, there are limits to the circularity of an economy because of the laws of thermodynamics.	Considering the materials that dissipate and are, therefore, impossible to recycle, Andorra's recycling rate decreases from 23% to 10%.
Externalisation	Andorra's strategy for sustainability is based on a "production-based approach" perspective.	Social-economic systems are dissipative systems that must be open. Therefore, it is also essential to consider the environmental pressures caused by domestic demand regardless of where they occur.	Andorra relies on externalisation practices to achieve local sustainability goals.
Growthism	Economic growth is seen as positive and necessary, a win-win solution to all problems.	The unlimited growth of production (and consumption) collides with the planet's biophysical limits related to resource depletion on the input side and waste absorption on the output side.	The commitment to reduce emissions is modest from a hypothetical scenario that assumes growth. Expected emissions by 2030 are 334 Gg CO_2eq, 34% higher than in 1990.

The current dominant narratives embedded in the conventional framework led to implausible assumptions about the validity of the proposed policies and indicators. For instance, it is argued that improvements in energy efficiency will lead irremediably to less consumption of energy, that integrating intermitting electric sources in centralised grids is not problematic and will contribute univocally to great energy sovereignty or that a circular economy is possible, and not contradicts the fundamental laws of thermodynamics. On the contrary, the adoption of a metabolic framework flags that an ecological transition in the strict sense will only be possible if the flow of energy and materials (what ecological economists call throughput) or metabolic flow decreases. Substantial reductions in the societal metabolism can be expected not so much from technological progress but rather from complex systemic changes such as demographic change (e.g. a smaller population may require smaller flows to be maintained), institutional arrangements (capitalism does not seem adequate because its growth imperatives) or radical changes in consumption patterns associated with a different integrated set of social practices (moving towards sustainable consumption, which means less and better consumption).

As proposed by Giampietro and Bukkens (2022), it is time to move from a strategy of governance *of* complexity (i.e. solving the problems using a narrow epistemic box with analysis generated by implausible socio-technical imaginaries) to a strategy of governance *in* complexity (i.e. analysing different aspects of the issues considered and acknowledging the coexistence of non-equivalent legitimate concerns and relevant narratives, expanding the inclusiveness of a given epistemic box). Moreover, we must always recognise that dominant narratives are grounded in imaginaries that rely on values, emotions, and expectations. These narratives generate an epistemic barrier controlling the accepted claims about social facts within the political sphere. This issue implies that the existing dominance of narratives and imaginaries in policy circles is not something that can be changed by providing “better” evidence based on a solid biophysical analysis or by speaking a different “truth” to power (Di Felice et al., 2021b). Still, questioning dominant narratives can be seen as a form of critical practice (Bacchi and Eveline, 2006). For this to have political and material ramifications, discussion with wider audiences is necessary. The truth is that there are no straightforward solutions to climate change and other wicked sustainability problems. Sustainability issues ultimately require understanding, social discussion, compassion, and sacrifices for all of us.

6.5. Chapter references.

Agricultural Department, 2019. Agricultural and livestock statistics [WWW Document]. https://www.agricultura.ad/estadistiques (accessed 24 Juny 2024)

Aguilar-Lopez, F., Lauinger, D., Vuille, F., Müller, D.B., 2024. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. Nat. Commun. 2024 151 15, 1–11. https://doi.org/10.1038/s41467-024-48554-0

Agusdinata, D.B., Liu, W., Eakin, H., Romero, H., 2018. Socio-environmental impacts of lithium mineral extraction: towards a research agenda. Environ. Res. Lett. 13, 123001. https://doi.org/10.1088/1748-9326/AAE9B1

Ahl, V., Allen, T.F.H., 1996. Hierarchy Theory. Columbia University Press, New York.

Almazán, A., Valero, Antonio, Valero, Alicia, 2021. Thanatia. Los límites minerales del planeta. Icaria Editorial, Barcelona.

Andorra Business, 2023. Advantages of investing in a business in Andorra [WWW Document]. https://www.andorrabusiness.com/en/invest/advantages-investing-business/ (accessed 26 Juny 2024)

Andorran Government, 2020. Pla Nacional de Residus. Balanç 2001-2020. Govern d'Andorra, Andorra la Vella.

Andreucci, D., McDonough, T., 2015. Capitalism, in D'Alisa, G., Demaria, F., Kallis, G. (Eds.), Degrowth: A Vocabulary for a New Era. Routledge, New York, pp. 59–62.

Angelo, H., Wachsmuth, D., 2015. Urbanizing Urban Political Ecology: A Critique of Methodological Cityism. Int. J. Urban Reg. Res. 39, 16–27. https://doi.org/10.1111/1468-2427.12105

Arenas, L., Naredo, J.M., Riechmann, J., 2022. Bioeconomía para el siglo XXI. Actualidad de Nicholas Georgescu-Roegen. Los Libros de la Catarata, Madrid.

Arendt, H., 1959. The Human Condition. University of Chicago Press, Chicago.

Bacchi, C., Eveline, J., 2006. What's the problem represented to be?, in: Bacchi, C., Eveline, J. (Eds.), Mainstreaming Politics: Gendering Practices and Feminist Theory. University of Adelaide Press, Adelaide, pp. 111–138.

Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. 1 9, 495–504. https://doi.org/10.1038/s41893-018-0139-4

Bonaiuti, M., 2022. Actualidad del pensamiento de Georgescu-Roegen. La bioeconomía cincuenta años después de la publicación de "La ley de la entropía y el proceso económico," in: Arenas, L., Naredo, J.M., Riechmann, J. (Eds.), Bioeconomía Para El Siglo XXI. Fuhem Ecosocial y Libros de la Catarata, Madrid, pp. 77–93.

BOPA, 2018. Llei 21/2018, del 13 de setembre, d'impuls de la transició energètica i del canvi climàtic (Litecc). Butlletí Oficial del Principat d'Andorra, Andorra la Vella.

Calwell, C., 2010. Is efficient sufficient? The case for shifting our emphasis in energy specifications to progressive efficiency and sufficiency. European Council for an Energy Efficient Economy, Stockholm. http://www. eceee. org/sufficiency/eceee_Progressive_Efficiency. pdf.

Carnot, N.L.S., 1897. Reflections on the Motive Power of Heat. John Wiley & Sons, London.

Chancel, L., Piketty, T., Saez, E., Zucman, G., 2022. World Inequality Report 2022. World Inequality Lab.

Daly, H., 2019. Growthism: its ecological, economic and ethical limits. Real-World Econ. Rev. 87, 9-22.

Daly, H., 2005. Economics in a full world. Sci. Am. 293, 78–85.

Department of Statistics, 2023. Economic and energy statistics [WWW Document]. https://www.estadistica.ad/portal/apps/sites/#/estadistica-ca/ (accessed 30 March 2024)

Di Felice, L.J., Cabello, V., Ripa, M., Madrid-Lopez, C., 2021a. Quantitative Storytelling: Science, Narratives, and Uncertainty in Nexus Innovations. Sci. Technol. Human Values. https://doi.org/10.1177/01622439211053819

Di Felice, L.J., Renner, A., Giampietro, M., 2021b. Why should the EU implement electric vehicles? Viewing the relationship between evidence and dominant policy solutions through the lens of complexity. Environ. Sci. Policy 123, 1–10. https://doi.org/10.1016/j.envsci.2021.05.002

Dunlop, T., 2022. Energy efficiency: The evolution of a motherhood concept. Soc. Stud. Sci. 52, 710–732. https://doi.org/10.1177/03063127221096171

EMF, 2024. What is a circular economy? [WWW Document]. Ellen MacArthur Found. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview#:~:text=The circular economy is a,remanufacture%2C recycling%2C and composting (accessed 23 March 2024)

European Commission, 2020. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability - COM/2020/474 final. Brussels.

European Commission, 2015. Closing the Loop - An EU Action Plan for the Circular Economy. Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2015) 614 Final. Brussels.

European Commission, 2012. Energy Road Map 2050. Luxemburg.

Eurostat, 2024. EU exported 32 million tonnes of waste in 2022 [WWW Document]. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240118-1 (accessed 12 March 2024)

FEDA, 2022. Memòria de sostenibilitat 2022. Forces Elèctriques d'Andorra, Andorra la Vella.

FEDA, 2021. Memòria de sostenibilitat. Forces Elèctriques d'Andorra, Andorra la Vella.

FEDA, 2020. Memòria de sostenibilitat 2020. Forces Elèctriques d'Andorra, Andorra la Vella.

FEDA, 2019. FEDA. Memòria de sostenibilitat 2019. Forces Elèctriques d'Andorra, Andorra la Vella.

Flexer, V., Baspineiro, C.F., Galli, C.I., 2018. Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. Sci. Total Environ. 639, 1188–1204. https://doi.org/10.1016/J.SCITOTENV.2018.05.223

Foucault, M., 2005. The Order of Things. Routledge, London.

Funtowicz, S., Ravetz, J., 1994. The Worth of a Songbird: Ecological Economics as a post-normal Science. Ecol. Econ. 10, 197–207.

Funtowicz, S., Ravetz, J., 1993. Science for the post-normal age. Futures 25, 735–755.

Gálvez-Martos, J.L., Istrate, I.R., García, D., 2018. Estudio de perspectiva de economía circular en la gestión de baterías de coche eléctrico en su fin de vida, in: CONAMA-Congreso Nacional Del Medio Ambiente.

Gartman, D., 2004. Three Ages of the Automobile: The Cultural Logics of The Car. Theory, Cult. Soc. 21, 169–195. https://doi.org/10.1177/0263276404046066

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environ. Innov. Soc. Transitions 1, 24–40. https://doi.org/10.1016/J.EIST.2011.02.002

Giampietro, M., 2021. Implications of Complexity Theory. Visions Sustain. 2021, 31–42. https://doi.org/10.13135/2384-8677/5995

Giampietro, M., 2019. On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth. Ecol. Econ. 162, 143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001.

Giampietro, M., 2018. Perception and representation of the resource nexus at the interface between society and the natural environment. Sustainability 10, 1–17. https://doi.org/10.3390/su10072545

Giampietro, M., Bukkens, S.G.F., 2022. Knowledge claims in European Union energy policies: Unknown knows and uncomfortable awareness. Energy Res. Soc. Sci. 91. https://doi.org/10.1016/j.erss.2022.102739

Giampietro, M., Cadillo-Benalcazar, J.J., Di Felice, L.J., Manfroni, M., Pérez-Sánchez, L., Renner, A., Ripa, M., Velasco-Fernández, R., Bukkens, S.G.F., 2020. Report on the Experience of Applications of the Nexus Structuring Space in Quantitative Storytelling. MAGIC (H2020–GA 689669) Project Deliverable 4.4, 30 August 2020.

Giampietro, M., Funtowicz, S., 2020. From elite folk science to the policy legend of the circular economy. Environ. Sci. Policy 109, 64–72. https://doi.org/10.1016/j.envsci.2020.04.012

Giampietro, M., Mayumi, K., 2018. Unravelling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. Front. Energy Res. 6, 1–13. https://doi.org/10.3389/fenrg.2018.00026

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London.

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Societies : Where Economists Fall Short. Routledge, London.

Giampietro, M., Renner, A., 2020. The Generation of Meaning and Preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria, in: Braha, D., et al. (Ed.), Unifying

Themes in Complex Systems X: Proceedings of the Tenth International Conference on Complex Systems. Springer (Series: Springer Proceedings in Complexity), Cham, Switzerland.

González-Reyes, L., 2022. Crisis energética. Papeles Relac. Ecosociales y Cambio Glob. 156, 67–78.

Gowdy, J., 2020. Our hunter-gatherer future: Climate change, agriculture and uncivilization. Futures 115, 102488. https://doi.org/10.1016/J.FUTURES.2019.102488

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/JIEC.12244

Haberl, H., Schmid, M., Haas, W., Wiedenhofer, D., Rau, H., Winiwarter, V., 2021. Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism. Ecol. Econ. 182, 106949. https://doi.org/10.1016/J.ECOLECON.2021.106949

Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D.J., Hearty, P.J., Hoegh-Guldberg, O., Hsu, S.L., Parmesan, C., Rockstrom, J., Rohling, E.J., Sachs, J., Smith, P., Steffen, K., Van Susteren, L., Von Schuckmann, K., Zachos, J.C., 2013. Assessing “Dangerous Climate Change”: Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature. PLoS One 8, e81648. https://doi.org/10.1371/JOURNAL.PONE.0081648

Harvey, D., 2019. La lógica geográfica del capitalismo. Icaria Editorial, Barcelona.

Harvey, D., 2010. A Companion to Marx’s Capital. Verso, London-New York.

Hausknost, D., 2020. The environmental state and the glass ceiling of transformation. Env. Polit. 29, 17–37. https://doi.org/10.1080/09644016.2019.1680062

Head, B.W., 2022. Wicked Problems in Public Policy: Understanding and Responding to Complex Challenges. Palgrave Macmillan, Cham.

Heredia, F., Martinez, A.L., Surraco Urtubey, V., 2020. The importance of lithium for achieving a low-carbon future: overview of the lithium extraction in the ‘Lithium Triangle.’ J. Energy Nat. Resour. Law 213–236. https://doi.org/10.1080/02646811.2020.1784565

Hickel, J., Dorninger, C., Wieland, H., Suwandi, I., 2022a. Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015. Glob. Environ. Chang. 73, 102467. https://doi.org/10.1016/J.GLOENVCHA.2022.102467

Hickel, J., Kallis, G., Jackson, T., O’Neill, D.W., Schor, J.B., Steinberger, J.K., Victor, P.A., Ürge-Vorsatz, D., 2022b. Degrowth can work — Here’s how science can help. Nature 612, 400–403. https://doi.org/10.1038/d41586-022-04412-x

Hobson, K., 2002. Competing Discourses of Sustainable Consumption: Does the “Rationalisation of Lifestyles” Make Sense? Env. Polit. 11, 95–120. https://doi.org/10.1080/714000601

Holgersen, S., Malm, A., 2015. “green fix” as crisis management. or, in which world is Malmö the world’s greenest city? Geogr. Ann. Ser. B, Hum. Geogr. 97, 275–290.

https://doi.org/10.1111/GEOB.12081

IEA, 2021. The Role of Critical Minerals in Clean Energy Transitions. World Energy Outlook Special Report, International Energy Agency.

INSIDEEVs, 2019. 91% Of Lithium For Lithium-Ion Batteries Comes From Three Countries [WWW Document]. https://insideevs.com/news/372133/91-of-lithium-three-countries/ (accessed 12 Juny 2024)

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Jasanoff, S., Kim, S.H., 2015. Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power. University of Chicago Press, Chicago. https://doi.org/10.7208/9780226276663

Jevons, W.S., 1865. The Coal Question. An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal Mines. August M. Kelley, New York.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J. et al., 2001. Sustainability Science. Science. 292, 641–642. https://doi.org/https://doi.org/10.1126/science.1059386

Keyßer, L.T., Lenzen, M., 2021. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat. Commun. 12, 2676. https://doi.org/10.1038/s41467-021-22884-9

Koehler, J., Geels, F., Kern, F., Onsongo, E., Wieczorek, A., Alkemaade, F., Avelino, F., Bergek, A., Boons, F., Bulkeley, H., Fuenfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Ki-vimaa, P., Markard, J., Martiskainen, M., McMeekin, A., Susan Mühle-meier, M., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., van den Bergh, J., Welch, D., Wells, P., 2017. A research agenda for the Sustainability Transitions Research Network, STRN Working Group, STRN. https://doi.org/10.2/JQUERY.MIN.JS

Kovacic, Z., 2015. Complexity theory in quality assessment. PhD Thesis, Universitat Autònoma de Barcelona (UAB).

Krähmer, K., 2020. Are green cities sustainable? A degrowth critique of sustainable urban development in Copenhagen. Eur. Plan. Stud. 29, 1272–1289. https://doi.org/10.1080/09654313.2020.1841119

Lakoff, G., 2010. Why it matters how we frame the environment. Environ. Commun. A J. Nat. Cult. 4, 70–81. https://doi.org/10.1080/17524030903529749.

Lawrence, M., Homer-Dixon, T., Janzwood, S., Rockstöm, J., Renn, O. & Donges, J. F. (2024). Global polycrisis: the causal mechanisms of crisis entanglement. Global Sustainability, 7, e6. https://doi.org/10.1017/SUS.2024.1

Levidow, L., 2013. EU criteria for sustainable biofuels: Accounting for carbon, depoliticising plunder. Geoforum 44, 211–223. https://doi.org/10.1016/J.GEOFORUM.2012.09.005

MAGIC Consortium, T., 2020. The Nexus Times. Megaloceros Press, Bergen.

Manfroni, M., Velasco-Fernández, R., Pérez-Sánchez, L., Bukkens, S.G.F., Giampietro, M.,

2021. The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth. Ecol. Econ. 190, 107183. https://doi.org/10.1016/J.ECOLECON.2021.107183

Martinez-Alier, J., 1987. Ecological Economics. Blackwell, Oxford/New York.

Mayumi, K., Renner, A., 2023. Reconsidering the Privileged Powers of Banks. Foundations of Sovereign Money, Wealth and Real Capital for Sustainability. Palgrave Macmillan, Singapore.

Mcadam, D., Tarrow, S., Tilly, C., 2003. Dynamics of Contention. Soc. Mov. Stud. 2, 99–102. https://doi.org/10.1080/14742837.2003.10035370

Miquel, C., Cuyàs, M., Boneta, A., 2021. Cuarto informe bianual de actualización de Andorra ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Govern d’Andorra, Andorra la Vella.

Moore, J.W., 2015. Capitalism in the Web of Life: Ecology and the Accumulation of Capital. Verso, London-New York.

Munda, G., 2008. Social Multi-Criteria Evaluation for a Sustainable Economy. Springer, Berlin.

Naredo, J.M., 2019. Taxonomía del Lucro. Siglo XXI, Madrid.

Naredo, J.M., 2015. La Economía en Evolución : Historia y Perspectivas de las Categorías Básicas del Pensamiento Económico (4aed.). Siglo XXI, Madrid.

O’Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 2018 12 1, 88–95. https://doi.org/10.1038/s41893-018-0021-4

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Koukkanen, A., Spangenberg, J.H., 2019. Decoupling Debunked: Evidence and arguments against green growth as a sole strategy for sustainability. European Environmental Bureau.

Peñasco, C., Díaz-Anadón, L., 2023. Assessing the effectiveness of energy efficiency measures in the residential sector gas consumption through dynamic treatment effects: Evidence from England and Wales. Energy Econ. 117, 106435. https://doi.org/10.1016/J.ENECO.2022.106435

Prats, F., Herrero, Y., Torrego, A., 2016. La Gran Encrucijada. Sobre la crisis ecosocial y el cambio de ciclo histórico. Libros en Acción, Madrid.

Princen, T., 2005. The logic of sufficiency. MIT Press, Cambridge.

Pulido-Sánchez, D., Capellán-Pérez, I., Mediavilla-Pascual, M., De-Castro-Carranza, C., Frechoso-Escudero, F., 2021. Analysis of the material requirements of global electricity mobility. Dyna 96.

Renner, A., Giampietro, M., 2020. Socio-technical discourses of European electricity decarbonization: Contesting narrative credibility and legitimacy with quantitative story-telling. Energy Res. Soc. Sci. 59, 101279. https://doi.org/10.1016/j.erss.2019.101279

Reuter, M.A., Schaik, A., Ballester, M., 2018. Limits of the Circular Economy: Fairphone Modular Design Pushing the Limits. World Metall. – ERZMETALL 71, 68–79.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9. https://doi.org/10.1126/sciadv.adh2458

Rittel, H.W., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169. https://doi.org/10.1007/BF01405730

Roca-Jusmet, J., Padilla-Rosa, E., 2021. Globalisation and responsibility in the ecological problems. J. Crit. Econ. 31, 1–18.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol. Soc. 14. https://doi.org/10.5751/ES-03180-140232

Russell, C., Lawrence, M., Cullerton, K., Baker, P., 2020. The political construction of public health nutrition problems: A framing analysis of parliamentary debates on junk-food marketing to children in Australia. Public Health Nutr. 23, 2041–2052. https://doi.org/10.1017/S1368980019003628

Seibert, M.K., Rees, W.E., 2021. Through the Eye of a Needle: An Eco-Heterodox Perspective on the Renewable Energy Transition. Energies 2021, Vol. 14, Page 4508 14, 4508. https://doi.org/10.3390/EN14154508

Shove, E., 2018. What is wrong with energy efficiency? Build. Res. Inf. 46, 779–789. https://doi.org/10.1080/09613218.2017.1361746

Smil, V. 2016a. Energy Transitions. Bloomsbury Publishing, London.

Smil, V., 2016b. What I see when I see a wind turbine [Numbers Don’t Lie]. IEEE Spectr. 53, 27. https://doi.org/10.1109/MSPEC.2016.7420393

Smil, V., 2015. Power Density: A key to understanding energy sources and uses. MIT Press, Cambridge.

Smil, V., 2008. Energy in Nature and Society: General Energetics of Complex Systems. MIT Press, Cambridge.

Sorrell, S., 2009. Jevons’ Paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy 37, 1456–1469. https://doi.org/10.1016/J.ENPOL.2008.12.003

Steffen, W., Rockström, J., Richarson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Cricifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhube, H.J., 2018. Trajectories of the Earth System in the Anthropocene. PNAS 115, 8252–8259. https://doi.org/10.1073/pnas.1810141115

Swyngedouw, E., 2010. Impossible Sustainability and the Post-Political Condition, in: Cerreta, M., Concilio, G., Monno, V. (Eds.), Making Strategies in Spatial Planning. Urban and Landscape Perspectives, Vol 9. Springer, Dordrecht, pp. 185–205. https://doi.org/10.1007/978-90-481-3106-8_11

Tainter, J.A., 2006. Social complexity and sustainability. Ecol. Complex. 3, 91–103. https://doi.org/10.1016/j.ecocom.2005.07.004

Tarascon, J.M., 2010. Is lithium the new gold? Nat. Chem. 2010 26 2, 510–510. https://doi.org/10.1038/nchem.680

Travesset-Baro, O., 2017. Prospectiva energètica al Principat d'Andorra. Model integrat d'avaluació de la seguretat energètica per a la transició cap a un escenari sostenibilista. PhD Thesis, Universitat Politècnica de Catalunya.

UN, 2015. Transforming our World: The 2030 Agenda for Sustainable Development A/RES/70/1. United Nations General Assembly.

UNEP, 2011. Recycling Rates of Metals - A Status Report. Working Group on the Global Metal Flows to the International Resource Panel. United Nations Environment Programme.

UNFCCC, 2015. Adoption of the Paris Agreement. United Nations Framework Convention on Climate Change.

Valero, Alicia, Valero, Antonio, Calvo, G., 2021. Summary and critical review of the International Energy Agency's special report: The role of critical minerals in clean energy transitions. Rev. Metal. 57. https://doi.org/10.3989/revmetalm.197

Valero, Alicia, Calvo, G., Valero, Antonio, 2021. Thanatia : límites materiales de la transición energética. Prensas de la Universidad de Zaragoza, Zaragoza.

Valero, Alicia, Valero, Antonio, Calvo, G., Ortega, A., 2018. Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev. 93, 178–200. https://doi.org/10.1016/j.rser.2018.05.041.

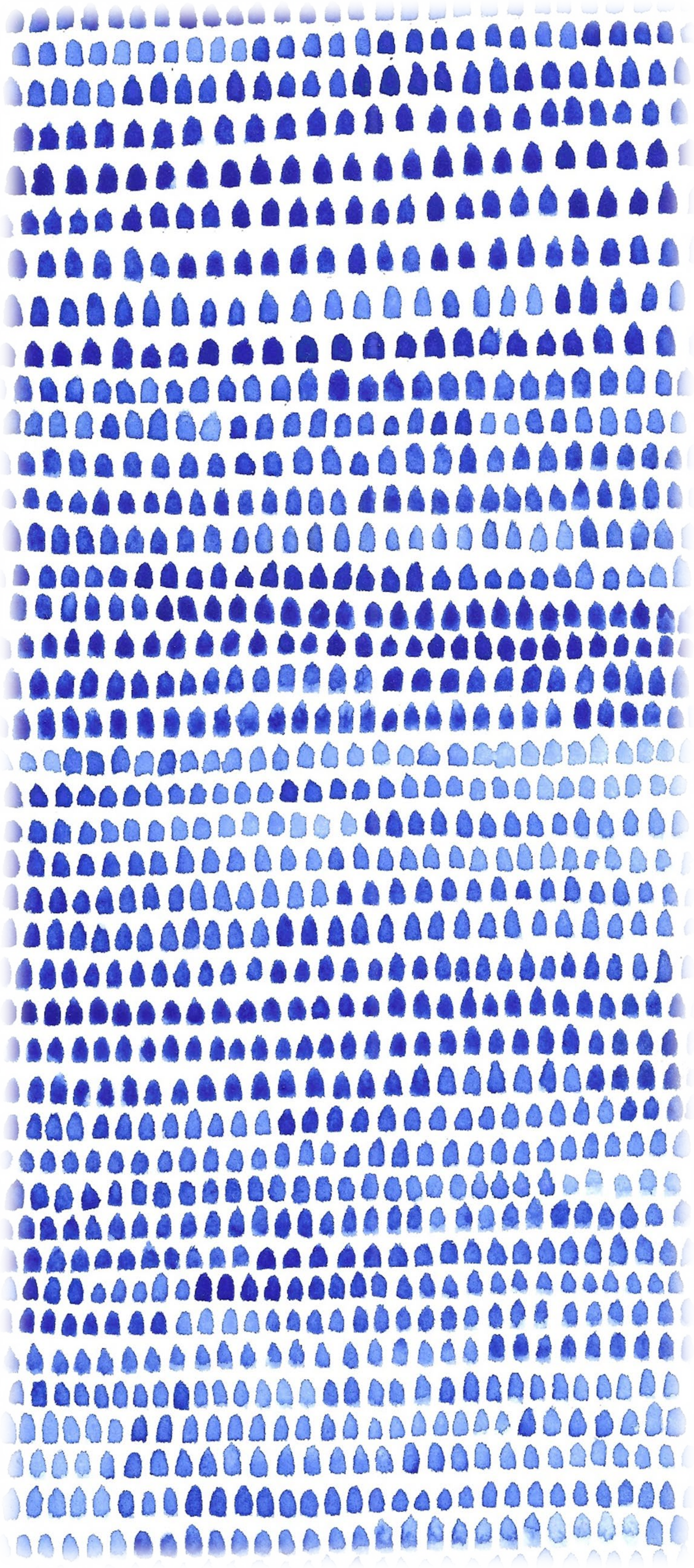
Velasco-Fernández, R., Dunlop, T., Giampietro, M., 2020. Fallacies of energy efficiency indicators: Recognizing the complexity of the metabolic pattern of the economy. Energy Policy 137. https://doi.org/10.1016/j.enpol.2019.111089

Velasco-Fernández, R., Pérez, A., 2022. Minerals crítics en conflicte i alternatives per la justícia global des de la compra pública: el cas del vehicle elèctric. Medicus Mundi Mediterrània, Barcelona.

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nat. Commun. 3107. https://doi.org/10.1038/s41467-020-16941-y

Xu, C., Behrens, P., Gasper, P., Smith, K., Hu, M., Tukker, A., Steubing, B., 2023. Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030. Nat. Commun. 2023 141 14, 1–11. https://doi.org/10.1038/s41467-022-35393-0

Chapter 7



7. Conclusions.

> “Si, como creemos la mayoría de nosotros,
> tenemos la capacidad de modelar el mundo
> de acuerdo con nuestros sueños y deseos,
> ¿por qué colectivamente lo hemos convertido en tal caos?
> Nuestro mundo social y físico puede y debe hacerse,
> rehacerse y, si sale mal,
> rehacerse una vez más.
> Por dónde empezar y qué se debe hacer
> son las cuestiones clave”.
> David Harvey[*].

7.1. Answering the research questions.

It is time to summarise and respond to the central research questions, particularly emphasising the critical methodological insights and significant outcomes from the Andorra case study. As stated in Chapter 1, the research gap associated with this dissertation was:

- ➢ How can a meaningful analysis be designed to account for critical relationships between society and the environment while addressing various types of limits?

This research gap is thoroughly explored through three distinct research questions. The first of these is:

- ◊ Is it possible to avoid the excessive simplifications of conventional economics when studying the sustainability of a given social-ecological system?

I have critically appraised conventional economics regarding sustainability issues to answer this question. This analysis is presented in Chapter 2, where I stress that conventional economics’ main drawback has ontological roots. The environment is non-existent in its fundamental vision of the economic process. Thus, this hegemonic vision has produced a distorted worldview where social and economic structures’ dependence on a biophysical reality is systematically ignored, overlooking the ecological processes’ crucial role. What is essential for sustainability is that this fundamental vision has no power of discrimination or anticipation. It does not enable mapping the relationships between the economy and the surrounding environment. At best, standard procedures for analysing environmental problems consist of partial internalisations of externalities

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[*] Extract belonging to Harvey, D. (2012). *Espacios de Esperanza*. Akal, Madrid, p. 318.

and assigning arbitrary monetary values to environmental goods and services. However, most environmental goods and services are not excludable and nonrival, resisting monetary valuation and integration into the market mechanism. This leads to unsatisfactory outcomes from a scientific perspective. Generally, ecological systems are neither observable nor controllable through market prices, rendering conventional economic policies often inadequate when addressing sustainability issues. Moreover, extending the measuring rod of money to encompass all aspects of reality, as conventional economics frequently attempts, raises several sustainability-related concerns: (i) intergenerational concerns arising from the fact that the well-being of future generations, who are absent from current markets, is not captured in market exchange; (ii) incommensurability concerns entailing a rejection of both monetary and physical reductionism; (iii) institutional concerns forcing to consider issues of political power and cost-shifting processes; and (iv) financial concerns requiring addressing the loss of monetary aggregates to monitor the size of biophysical processes underlying actual market transactions.

After analysing the main shortcomings of conventional economics when studying the sustainability of a given system, I have explored possible solutions in Chapter 3, addressing the question:

◊ How does MuSIASEM provide a more effective approach to sustainability analysis?

In this chapter, I have illustrated how the selected methodological approach provides a holistic and integrated perspective on the complex interactions between societal and ecological systems. MuSIASEM is not the only available approach in sociometabolic research. Its peculiarity is that it is a substantive economic tool that acknowledges the incommensurability of values and describes societal metabolism across dimensions and scales with several biophysical and socioeconomic indicators. By doing so, MuSIASEM provides a comprehensive understanding of the interconnections and interdependencies of human and environmental systems, allowing for a more nuanced analysis of the challenges and opportunities associated with the sustainable development domain. In particular, the holistic and relational approach is crucial for identifying the mechanisms of socio-environmental cost-shifting, analysing the structural and functional relationships in social-ecological systems, uncovering scaling effects (such as the Jevons paradox), and capturing the systemic needs and dynamics that may be overlooked through partial analysis affected by reductionism.

In contrast to conventional economics, the concept of state-pressure relations and the adoption of the flow-fund model enable an examination of the size of fund elements and their metabolic rates (i.e. flow rates per unit of fund) in the anthroposphere compared to the size of the ecological funds and their metabolic rates in the embedding environment. This combination of extensive and intensive variables in the analysis allows for identifying the unsustainable use of biophysical resources. Therefore, MuSIASEM makes these relationships explicit, facilitating their mapping and enabling a robust sustainability analysis. More specifically, MuSIASEM analysis provides several key insights: (i) it identifies which elements have to be preserved and reproduced inside the anthroposphere, including determining their size; (ii) it assesses the specific flows that these elements require per unit of size; (iii) it recognises the functions maintained over the analytical that are associated with valuable tasks for society; (iv) it categorises environmental pressures and impacts by tracking the connection between the consumption of secondary inputs in the anthroposphere and the requirement of primary supply and sink in the ecosphere; and (v) it differentiates between internal sustainability issues, associated to viability, and external sustainability issues, concerning feasibility. In conclusion, MuSIASEM is a very promising tool for more effective sustainability analysis. However, it requires the capacity to handle, store, and process a vast amount of data, requiring a profile encompassing different typologies of expertise. Moreover, applying its protocols with the resulting semantic integration of different metrics requires a considerable effort to force different statistics to talk to each other, as Appendix A shows.

I have developed the analytical part of the dissertation in Chapters 4, 5, and 6 to answer the last research question:

◊ Do the results from Andorra's case study demonstrate the effectiveness of the proposed approach?

In this respect, I have conducted a sustainability assessment integrating multiple dimensions and scales of analysis. Thus, I have performed a nexus analysis diagnosticating the main biophysical requirements that allow the maintenance and reproduction of Andorra. The resulting characterisation of the metabolic pattern of Andorra was obtained using an end-use matrix and an environmental pressure matrix. I have also compared the metabolic pattern of Andorra with that of other neighbouring countries and that of Menorca, a region of high touristic specialisation (Chapter 4). Given the country's high openness and significant dependence on external resources, I have conducted an externalisation analysis to account for the nexus elements embodied in imported energy carriers and food products. These values were subsequently compared with those associated with the local consumption patterns of Andorra's energy and agricultural systems (Chapter 5).

The identity of a society encompasses not only its biophysical or tangible dimension where the structural and functional coupling between societal elements and their context occurs. There is also an immaterial dimension where collective shared values are formed, affecting the final expression of the society's metabolic pattern. In relation to this point, I first considered the conventional framework within Andorra's sustainable policy domain —specifically, how the original analysis is linked to a given set of narratives related to relevant concerns to be addressed, the display of particular policies and the use of specific indicators. Then, I have contrasted this framework against the findings obtained when adopting the metabolic narrative developed in this thesis (Chapter 6).

The nexus analysis in Chapter 4 has provided a systematic and multidimensional perspective of the nexus biophysical requirements of the different constituent components of Andorra to perform their functions. Andorra is an open system from a metabolic point of view. The country's economic activities are not solely determined by the resources within its physical boundaries. Andorra has a highly productive specialisation in the service sector, particularly in tourism and financial activities. However, it lacks a productive sector providing the goods and services necessary to maintain its identity. The household and the service and government sectors (the two large functional compartments) present a great outsourcing of resources. This results in a reduction of internal socio-environmental pressures and the externalisation of those pressures onto other social-ecological systems.

This analysis also underscores the complex relationship between economic productivity and environmental pressures. Sustaining dissipative structures, such as people and different types of land uses, while achieving economic performance is intricately linked to metabolic flows. In the case of Andorra, each inhabitant requires 109 GJ of energy (in gross energy requirement) per year or 129 m^3 of water for consumptive uses. Furthermore, each EUR of GVA is associated with using 5 MJ of energy, 6 litres of water, 0.2 $kgCO_2eq$ of GHG emissions and the generation of 0.1 kg of waste. Similarly, the production of residential space is tied to the use of 1 055 MJ/m^2 of energy (in gross energy requirement) and the consumption of 1 175 l/m^2 of water. Understanding this complex interplay between economic productivity and environmental pressure is crucial for sustainable development planning.

Andorra’s labour productivity per hour aligns with that of its neighbouring countries. However, due to the lack of an energy-intensive industrial sector, it has lower energy requirements per capita (109 GJ in gross energy requirement) and per hour in the productive sector (82 MJ/h in gross energy requirement) than its neighbouring countries and the average values for the EU. Besides, we can conclude that the country holds a high material standard of living in the residential sector, given its high exosomatic metabolic rate in the household sector (8.3 MJ/h). On the other hand, the per capita use of energy resources in Andorra is higher than in other tourist destinations such as Menorca (109 GJ per capita per year in gross energy requirement versus 87 GJ per capita per year). However, energy use in the service and government sector per hour of work is less intensive in Andorra compared to Menorca (82 MJ/h in gross energy requirement versus 110 MJ/h), mainly due to its limited transport service infrastructure. Consequently, future projects to extend these infrastructures have important implications for assessing progress towards meeting international agreements on climate and achieving a carbon-neutral economy.

Using relational analysis from the epistemological tool of the metabolic processor, Chapter 5 identifies externalised processes across multiple levels in Andorra’s energy and agricultural systems. In aggregate terms, results show the country’s high dependence on other territories. Andorra stands out by externalising seven times the working hours, 40 times the land and six times the water compared to the values of its local energy sector. Moreover, externalised energy processes emit 17 times more GHG emissions than components generating local energy supply. In addition, Andorra uses eight times more human activity, 15 times more land, 22 times more blue water and GHG emissions are multiplied by 7 in relation to the local agricultural system to maintain its endosomatic metabolism. These findings also shed light on decarbonisation policies and ethical concerns, suggesting that more attention should be paid to regulating the system’s openness since externalising displaces environmental deterioration and social conflicts.

The externalisation analysis has been challenging for three reasons: (i) the vast amount of data to be handled —raw customs data on food imports listed more than 1

400 Excel rows with different combined nomenclature codes; (ii) the lack of data availability, accessibility and quality concerning nexus variables associated with energy and food processes; and (iii) the lack of data at the level required to characterise Andorra's energy and agricultural systems. These considerations call for caution when drawing a solid conclusion from the results presented in the chapter.

Finally, Chapter 6, using a Quantitative Storytelling approach, explores the existence of an alternative framework based on a metabolic approach, which can be used to assess the quality of the conventional frame influenced by standard economics. Comparing non-equivalent approaches (i.e., conventional vs. metabolic) offers new insights revealing alternative knowledge claims that can enhance the quality of the debate within the sustainable development domain in Andorra.

By analysing the various narratives presented in the conventional framework, we find that efficiency is considered a panacea. Increases in efficiency are deemed practical solutions to reduce resource consumption and related emissions, and efficiency indicators are considered crucial measures of sustainability improvements. Similarly, renewable technologies are championed as win-win solutions, reducing dependence on fossil fuels while enhancing energy sovereignty. Electric cars are justified by the promises to lower GHG and pollution, and the circular economy in the field of waste is promoted for its ability to transform the traditional linear production and consumption process into a "closed loop" system. In this framework, economic growth is not only seen as necessary but as the solution to all problems. In contrast, an alternative framework grounded in a metabolic approach challenges these assumptions. It argues that efficiency indicators are irrelevant to sustainability analysis because what is essential for sustainability is to reduce the absolute amounts of energy and materials (considering the overall level of openness of an economy). Renewable technologies are deemed problematic when considering the characteristics of Andorra's environment and the lack of options for large-scale storage capacity. Similarly, the future of electric cars is fraught with uncertainty from a nexus biophysical perspective, and the strategy of the circular economy is criticised for overlooking the entropic nature of the economic process. Overall, metabolic narratives clearly indicate that unlimited economic growth is not viable as it inevitably clashes with the biophysical limits of the planet.

Based on a metabolic analysis, the findings question the validity of the mainstream proposed policies and indicators in Andorra's sustainable development domain. Current dominant narratives embedded in the conventional framework appear based on questionable assumptions about their effectiveness. For instance, while the energy intensity indicator decreased by 30% for 2012-2022, the gross energy requirements value —a relevant sustainability indicator— has only declined by 10%. The significant increase in renewable energy power capacity has had little effect on the country's energy sovereignty. Electric car penetration only accounts for 1% of the total fleet of vehicles, and Andorra's recycling rate is only 10% when considering the materials dissipate and therefore impossible to recycle. Moreover, the commitment to reduce emissions within a growth-driven scenario is insufficient. Adopting a metabolic framework indicates that a genuine ecological transition will require a substantial readjustment in the societal metabolism, necessitating complex systemic changes and radical changes in current social practices.

This last idea of the forced relation between sustainability and the realisation of complex changes forms the crux of these conclusions, synthesising the core message of the thesis. Although MuSIASEM is an eminently quantitative tool, its fundamental assumptions urge us to reflect on a crucial point: simply crunching more and more data with increasingly complicated models while remaining within the same epistemic box (i.e. the same set of narratives framing sustainability) will not yield new solutions to sustainability problems. In an interconnected world, the ecological dilemma may result from humanity's relentless pursuit of achieving too much. That is why the sustainability of human systems seems to require a subtle balance between efficiency —i.e. doing better according to what is known— and adaptability —changing the identity of the system and the resulting expression of a metabolic pattern in the face of changes in boundary conditions. In other words, it is not always the external world that has to be adjusted according to our wants. We must also learn how to adjust our wants to the constraints provided by the external world (as was done in ancient cultures before the intoxication produced by conventional economics). This entails looking reflexively at how we carry out our semiotic process that defines our social identity, the narratives to be used, and the relevant aspects of reality to be considered (Giampietro, 2024). With this in mind, we should approach the unilateral reliance on technological innovations to solve sustainability problems with a healthy dose of scepticism.

Sustainability solutions cannot simply be found through a lens of complexity. They must be created, negotiated, and nurtured through a political process. Biophysical constraints shape the range of possible and desirable options within this process. A central theme throughout the history of ecologism is the question of limits (Riechmann, 2024). This thesis continues along this path, striving to deepen our understanding of our sustainability predicament and to foster a sober discussion of radical imaginaries of change.

7.2. Looking forward.

Here, the thesis ends. An eminently descriptive and reflexive work has been done. The originality of the academic efforts is centred on two complementary strands:

- At the theoretical level, different concepts constituting the theoretical foundations of MuSIASEM, belonging to various fields of complexity science, have been synthesised, clarified, and discussed to facilitate MuSIASEM application. In turn, it has been emphasised how the different analytical tools in the approach contribute to tackling critical aspects of sustainability issues, for which mainstream analyses based on the fundamental vision of conventional economics provide unsatisfactory assessments.
- At the practical level, (i) the MuSIASEM methodology has been applied to the socioeconomic reality of Andorra for the first time, and (ii) a holistic analysis has been carried out integrating aspects which were previously analysed separately in other studies. Thus, the characterisation performed includes and complements works focusing solely on energy use (Pérez-Sánchez et al., 2019; Velasco-Fernández et al., 2020), studies that address different dimensions but do not consider the dependence on externalised processes (Marcos-Valls et al., 2020), and works that, while considering externalisation, focus only on energy (Di Felice et al., 2024; Ripa et al., 2021) or food (Cadillo-Benalcazar et al., 2020) without encompassing both endosomatic and exosomatic requirements. Additionally, the results obtained have been compared with other case studies for which data were available, helping to contextualise the analysis better. Finally, because human societies are autopoietic systems that build shared values to preserve and adapt their identity (Giampietro, 2024), “quantitative storytelling”, i.e. an analysis of the main narratives found in the field of sustainable development in Andorra supported by data, has been carried out.

However, new avenues of research lie ahead. At the Andorran scale, as discussed in Chapter 4, a breakdown of the biophysical requirements of the subsectors that comprise the service and government sector —especially those crucial to maintaining Andorra's identity, such as the hotel sector or ski areas— seems necessary for a more accurate assessment. Given the current lack of statistical information, it would be required to characterise these subsectors using bottom-op information, including the analysis of instances of types of structural elements and direct measurement of technical coefficients. Moreover, this analysis should account for allocating human activity more comprehensively. This means a parallel accounting that considers those working in the paid sector, as done in this thesis, and those using and paying for these services. Indeed, for many activities in the service sector, there is a simultaneous requirement of human activity both on the supply side (e.g. people working in a restaurant or bus drivers) and the demand side (e.g. restaurant customers or passengers taking the bus). An example of how this type of accounting could be was shown in the Progress Report (Larrabeiti-Rodríguez, 2021) for the hotel industry. Notwithstanding, it has been deleted from this thesis's final version as it needs a more rigorous approach in accounting terms.

Another exciting way of inquiring, given the distinctive characteristics of Andorra and the sensitivity of its metabolism to tourist fluctuations, is to perform a MuSIASEM analysis that goes beyond the usual annual calculation by distinguishing between different seasons. This assessment would make it possible to characterise the different metabolic requirements for each season (e.g. the high season of winter and summer and the low season of autumn and springtime), providing a more precise analysis of metabolic vulnerabilities. Such insights would improve the quality of the debate held in Chapter 5 on energy and food dependence on other territories. Furthermore, this type of analysis can be applied to other regions with economies heavily reliant on tourism.

During the preparation of Chapter 5, the challenges encountered in gathering reliable data to characterise Andorra's energy and agricultural systems led to an unresolved question: what is the maximum population that Andorra could sustain, in terms of endosomatic and exosomatic metabolism, relying solely on its internal resources? To address this question, it would be necessary to develop local metabolic processors for the energy and agricultural sectors using the most precise data from a bottom-up characterisation. This would allow us to determine the labour, land, water, and other resources required to produce a kilo of meat or one kilowatt-hour of electrical energy from Andorra and the maximum production capacity the country could support under various multidimensional limits. In addition, it could be possible to characterise not only current but also potential metabolic processors by determining the biophysical requirements of crops or energy generation technologies that could be introduced in the future in Andorra, using the MuSIASEM toolkit in anticipatory mode, as illustrated in Figure 7.1.

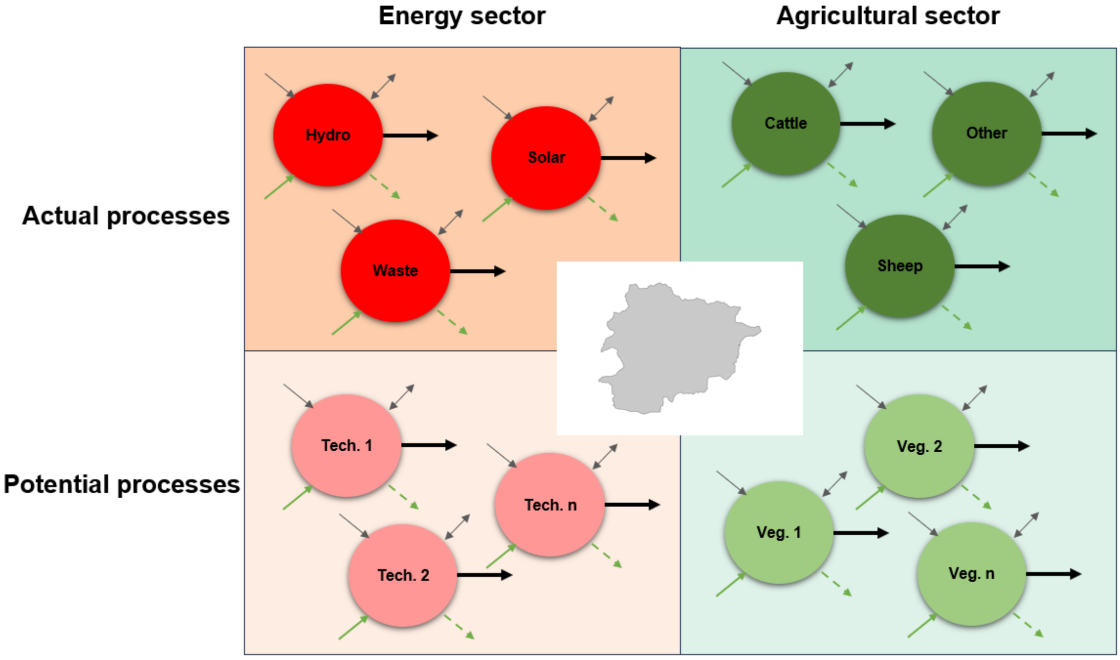

Figure 7.1. Potential study of actual and potential metabolic processors in Andorra. Tech: Technology; Veg: Vegetable. Source: own elaboration.

Future applications exceed the scale of Andorra. Change in our economic systems is inevitable. The only question is whether this change will come as a chaotic response to unforeseen disruptions in the global life support system or as a carefully planned transition toward a system that operates within the physical limits of a finite planet and the moral and ethical boundaries expressed in our values (Daly and Farley, 2011). The mainstream discourse of sustainable development sidesteps critical questions about how much is enough and the power dynamics driving exponential and unsustainable growth of consumption and material throughput. However, an analysis of the resource use and labour requirements needed to achieve a good life for everyone within the planetary boundaries is required, given the urgent need to reconcile human well-being and environmental sustainability. This idea can be found in many authors and lines of thought claiming to achieve sustainability, equity and human well-being, such as the prosperous way down (Odum and Odum, 2011), prosperity without growth (Jackson, 2009), simplicity (Alexander and McLeod, 2014), alternative worldviews (Riechmann, 2022), ecosocialism (Löwy, 2005), and degrowth (Hickel et al., 2022; Klitgaard, 2013; Schmelzer et al., 2022) and post-growth (Fioramonti et al., 2022; Hardt et al., 2021) narratives. The fundamental question that arises is: what alternative set of social practices could enable a good life with reduced energy and material use? Or, as phrased in this thesis, how will new desirability constraints be integrated with different viability and feasibility constraints? The fact is that there is a significant lack of quantitative assessments of the possible trade-offs that can be associated with such a proposal. A multiscale integrated approach to analysing different scenarios could be beneficial. It could also contribute to ongoing research projects recently launched to fill this gap (MAPS project, 2024; REAL project, 2024) or future lines of research.

In line with the above, given the essential character of care activities within human well-being, the study of care metabolism appears like an exciting field to explore. Care metabolism refers to the contextualised use of resources associated with self-care and support for others, including children, elderly individuals, people with disabilities, and those sick or injured (Velasco-Fernández, 2024). Conversely to conventional economics, where human activity outside the narrow limits of markets is hidden, analysis from the perspective of societal metabolism stresses the importance of the activities in the household sector as necessary for societal maintenance and reproduction. Care activities are predominantly performed through unpaid household work, mainly by women, migrant workers, and low-income people. Informal and precarious work is usual in the care sector despite its substantial contribution to overall societal well-being. Consequently, a comprehensive assessment of care metabolism would provide valuable insights into the overlapping dynamics of discrimination and privilege in providing and enjoying care services. It would also supply an information space for facilitating discussions on different post-growth policies and their implications for time use, workloads, energy, materials, and emissions, among other biophysical indicators.

7.3. Chapter references.

Alexander, S., McLeod, A., 2014. Simply Living in History: Pioneers of the Deep Future. Simplicity Institute, Melbourne.

Cadillo-Benalcazar, J.J., Renner, A., Giampietro, M., 2020. A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe. J. Environ. Manage. 271, 110944. https://doi.org/10.1016/j.jenvman.2020.110944

Daly, H., Farley, J., 2011. Ecological economics : principles and applications (2nd edition). Island Press, Washington.

Di Felice, L.J., Pérez-Sánchez, L., Manfroni, M., Giampietro, M., 2024. Towards nexus thinking in energy systems modelling: A multi-scale, embodied perspective. Energy Policy 187, 114052. https://doi.org/10.1016/J.ENPOL.2024.114052

Fioramonti, L., Coscieme, L., Costanza, R., Kubiszewski, I., Trebeck, K., Wallis, S., Roberts, D., Mortensen, L.F., Pickett, K.E., Wilkinson, R., Ragnarsdottír, K.V., McGlade, J., Lovins, H., De Vogli, R., 2022. Wellbeing economy: An effective paradigm to mainstream post-growth policies? Ecol. Econ. 192, 107261. https://doi.org/10.1016/J.ECOLECON.2021.107261

Giampietro, M., 2024. Combining biosemiotics and post-normal science to study the formation and adaptation of the identity of modern society. Futures 161, 103414. https://doi.org/10.1016/J.FUTURES.2024.103414

Hardt, L., Barrett, J., Taylor, P.G., Foxon, T.J., 2021. What structural change is needed for a post-growth economy: A framework of analysis and empirical evidence. Ecol. Econ. 179, 106845. https://doi.org/10.1016/J.ECOLECON.2020.106845

Hickel, J., Kallis, G., Jackson, T., O'Neill, D.W., Schor, J.B., Steinberger, J.K., Victor, P.A., Ürge-Vorsatz, D., 2022. Degrowth can work — Here's how science can help. Nature 612, 400–403. https://doi.org/10.1038/d41586-022-04412-x

Jackson, T., 2009. Prosperity without Growth. Economics for a Finite Planet. Routledge, London.

Klitgaard, K., 2013. Heterodox Political Economy and the Degrowth Perspective. Sustainability 5, 276–297. https://doi.org/10.3390/SU5010276

Larrabeiti-Rodríguez, J.J., 2021. Integrated analysis of the water-energy-food nexus of Andorra under the MuSIASEM approach for the transition to a more sustainable model. Sant Julià de Lòria (Andorra).

Löwy, M., 2005. What is ecosocialism? Capital. Nature, Social. 16, 15–24. https://doi.org/10.1080/10455750500108237/ASSET//CMS/ASSET/4387B3F3-743F-44DA-A821-1CF5FA298284/10455750500108237.FP.PNG

MAPS project, 2024. Models, Assessment, and Policies for Sustainability [WWW Document]. https://portalrecerca.uab.cat/en/projects/models-assessment-and-policies-for-sustainability-2 (accessed 22 August 2024)

Marcos-Valls, A., Kovacic, Z., Giampietro, M., Kallis, G., Rieradevall, J., 2020. Isolated yet open: A metabolic analysis of Menorca. Sci. Total Environ. 738, 139221. https://doi.org/10.1016/j.scitotenv.2020.139221

Odum, H.T., Odum, E.C., 2011. A prosperous way down. The University Press of Colorado, Niwot.

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., Ripa, M., 2019. Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. Energy Policy 124, 13–22. https://doi.org/10.1016/j.enpol.2018.09.028

REAL project, 2024. European project to explore pathways towards post-growth economics [WWW Document]. https://www.uab.cat/web/sala-de-premsa-icta-uab/detall-noticia/european-project-to-explore-pathways-towards-post-growth-economics-1345819915004.html?detid=1345872411651 (accessed 22 August 2024)

Riechmann, J., 2024. Ecologismo: pasado y presente (con un par de ideas sobre el futuro). Los Libros de la Catarata, Madrid.

Riechmann, J., 2022. Simbioética. Homo Sapiens en el Entramado de la Vida. Plaza y Valdés, Madrid.

Ripa, M., Di Felice, L.J., Giampietro, M., 2021. The energy metabolism of post-industrial economies. A framework to account for externalization across scales. Energy 214, 118943. https://doi.org/10.1016/j.energy.2020.118943

Schmelzer, M., Vetter, A., Vansintjan, A., 2022. The future is degrowth: A guide to a world beyond capitalism. Verso, London-New York.

Velasco-Fernández, R., 2024. Care metabolism: a methodological framework for studying the biophysical foundations of care and its unequal distribution, in: Proceedings of the 10th International Degrowth Conference and the 15th Conference of the European Society for Ecological Economics (ESEE): Science, Technology, and Innovation beyond Growth. Cultivating Collective Creativity for a Sustainable Future. Pontevedra.

Velasco-Fernández, R., Pérez-Sánchez, L., Chen, L., Giampietro, M., 2020. A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. Energy Strateg. Rev. 32, 100562. https://doi.org/10.1016/j.esr.2020.100562

Appendix A.

The metabolic pattern of Andorra: a diagnosis

A1. Human Activity.

A1.1. Total Human Activity (THA) (Level N).

To know this value, it is first necessary to calculate the equivalent population (EP) from Andorran Government (2016a). The different categories appearing in Equation A1 can be found in the Department of Statistics (2019a):

$$EP = Resident\ population + 0.4 \cdot Frontier\ workers + \frac{180}{365} \cdot Seasonal\ workers + \frac{0.4}{365} \cdot Hikers + \frac{1}{365} \cdot Nights\ spent\ by\ tourists \quad \text{(A1)}$$

To convert the value of the population equivalent to hours of human activity, we must multiply by 8 760.

A 1.2. Paid work (PW) (levels N-1 and N-2).

The Department of Statistics (2019) meticulously collects workers' data for various economic activities. Each sector's total number of workers is calculated based on the annual average number of employees, considering the number of full-time employees each month. This yearly average accounts for foreign workers, who increase the workforce mainly between December and April, coinciding with skiing and winter tourism activities. The PW includes direct and indirect employment as well as self-employed and salaried workers. The economic subsectors of the AG, the ICM, and the SG were aggregated by considering the grouping shown in Table A1. Full-time contracts of 1 800 hours per year have been deemed to calculate the hours of self-employed and salaried workers. Moreover, using CRES (2018) data, an estimated 344 472 extra hours in the SG have been considered. This last number arises from considering a maximum of 426 overtime hours per worker per year and applying them to 6.6% of hotel workers, 4.5% of professional service workers and 3.6% of commercial workers.

A1.3. Other users (level N-1).

This category includes the hours of the frontier workers, plus the hours of hikers and nights spent by tourists, except for 16% of these last hours, which are considered to be tourists staying in private residences, according to information in the Department of Statistics (2019).

Table A1. Aggregation of groups in the PW. Own elaboration from Department of Statistics (2023).

PW aggregation	***Groups in statistics***
AG	A-“Agricultura, ramaderia, caça i silvicultura” B-“Pesca”
ICM	C-“Industries extractives” D-“Industries manufactureres” E-“Producció i distribución d’energia eléctrica, gas i aigua” F-“Construcció”
SG	G-“Comerç” H-“Hosteleria” I-“Transport i comunicacions” J-“Sistema financer” K-“Activitats inmobiliaries i serveis empresarials” L-“Administració pública i seguritat social” M-“Educació” N-“Activitats sanitàries, i veterinaries, serveis socials O-“Altres activitats socials i serveis personals” P-“Llars que ocupen personal domèstic” Q-“Organismes extraterritorials” T-“Treball domèstic a la comunitat”

A1.4. Household (HH) (level N-1).

This category is calculated by the difference between the hours of THA minus the hours of PW and other users.

A2. Land Uses.

Data about land uses is available in CENMA-IEA (2012). Andorra has an area of 46 770 hectares, of which only 1.71 % are urbanised areas. Considering the percentages of surfaces authorised for construction (Department of Statistics, 2019b), 59% are housing spaces and, therefore, belong to the HH. The area occupied by the PW has been calculated based on the following: (i) the space used for the AG corresponds to 4.40% of the total area of Andorra (Miquel et al., 2014); (ii) the space used for the ICM includes reservoirs and inland waters CENMA-IEA (2012) and the surface devoted to other buildings (17% of the surfaces authorised for construction); and (iii) the space used for the SG includes the 24% of the surfaces authorised for construction, 3 200 hectares of skiable surface (Miquel et al., 2014), and roads, sports and leisure areas, and bare areas (CENMA-IEA, 2012). The difference between the total area of Andorra and the space devoted to the HH and the PW is considered non-managed land.

A3. Economic Variables.

Economic variable data is sourced from the Department of Statistics (2023).

A4. Energy.

A4.1. Electricity.

The electricity values for the different functional compartments are sourced from the Department of Statistics (2023). The energy consumption allocated to the heading "*Altres distribuïdores*" has been distributed proportionally among the other items. Moreover, the percentages of electricity and heat consumption for the various sub-functional compartments in the HH are taken from Travesset-Baro (2017) and shown in Table A2.

Table A2. Percentages of electricity and heat consumption for various sub-functional compartments in the HH. Source: Travesset-Baro (2017).

HH sub-functional compartments	***Electricity €***	***Heat (H)***
Air Conditioning	0.004%	
Sanitary hot water	8.576%	15.515%
Heating	16.011%	84.485%
Cooking	18.197%	
Household electrical	51.362%	
Lightning	5.850%	

A4.2. Heat.

Domestic fuel, butane, and propane values have been obtained from the Department of Statistics (2023). According to Miquel et al. (2014), the quantities of butane and propane are evenly distributed between the HH and the SG. Moreover, the distribution of domestic fuel between the various societal compartments is as follows (Travesset-Baro, 2017): 32% in the HH, 2% in ICM, and 66% in SG.

A4.3. Fuel.

Of the quantities entered in the Department of Statistics (2023) for petrol and diesel fuel values, Travesset-Baro (2017) estimates that 20% of petrol imports and 51% of diesel imports are sold in Andorra as fuel tourism. By discounting these values, we get the fuel consumption inside the country that is associated with its social metabolism. From the same source, it is estimated that this consumption is distributed as follows: 80% is assigned to passenger cars, 15% to transport goods, 4% to transport passengers, and 1% to motorbikes. Given this information, the values associated with passenger cars and motorbikes have been assigned to the HH. Besides, 0.2% of transport goods to the AG, 9.8% of transport goods to the ICM, and 90% of transport goods and 100% of transport passengers to the SG.

A4.4. Gross Energy Requirements.

The GER is calculated by transforming the different energy carriers into Joules and applying the following conversion factors from Giampietro et al. (2013): 2.61 for electricity, 1.10 for heat, and 1.38 for fuel. The different results obtained from the conversion must be summed up to get the figure corresponding to the GER.

A5. Water.

Information on water use comes from the Andorran Government (2016b). Values from the item "*caudal captat*" have been utilised. Domestic uses have been computed as belonging to the HH, as well as the consumption of hotels, restaurants, and snow fields in the SG. The consumption of the waste treatment centre and a percentage of 0.29% of the total for the Massana, Escaldes and Andorra parishes have been assigned to the ICM, whereas the water consumption for agriculture and livestock to the AG. Under the "non-consumptive use" heading, water is used for hydroelectricity, artificial snow manufacturing, and aquaculture.

A6. Emissions.

The calculation of emissions is based on Travesset-Baró (2017), which considers the following emission factors for imported electricity: Spain, 302 gCO_2/kWh and France 44 gCO2/kWh. Moreover, the IPCC (2006) has identified the emission factors for utilised fuels.

References.

Andorran Government, 2016a. Revisió del Pla Nacional de Residus d'Andorra (2017-2020). Govern d'Andorra, Andorra la Vella.

Andorran Government, 2016b. Estudi per a l'elaboració anyal de l'inventari i quantificació de la despesa hídrica per usos del Principat d'Andorra-Any 2015. Govern d'Andorrra, Andorra la Vella.

CENMA-IEA, 2012. Memòria del mapa de cobertes del sòl d'Andorra (MCSA) de l'any 1972. Comparativa amb el MCSA de l'any 1995. Institut d'Estudis Andorrans, Sant Julià de Lòria.

CRES, 2018. Estudi sobre el mercat de treball d'Andorra. Centre de Recerca Sociològica, Andorra la Vella.

Department of Statistics, 2023. Economic and energy statistics [WWW Document]. https://www.estadistica.ad/portal/apps/sites/#/estadistica-ca/ (accessed 6 June 2023)

Department of Statistics, 2019a. Demographic, social and economic statistics [WWW Document]. https://www.estadistica.ad/portal/apps/sites/#/estadistica-en (accessed 6 June 2023)

Department of Statistics, 2019b. Superfície autoritzada [WWW Document]. http://www.estadistica.ad (accessed 4 April 2019)

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge, London. https://doi.org/10.4324/9780203107997

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Miquel, C., Armengol, J.L., Dobarro, J., Rovira, N., 2014. Premier Rapport Bisannuel de l'Andorre a la Convention Cadre des Nations Unies sur les Changements Climatiques. Andorra: Govern d'Andorra.

Travesset-Baro, O., 2017. Prospectiva energètica al Principat d'Andorra. Model integrat d'avaluació de la seguretat energètica per a la transició cap a un escenari sostenibilista. Universitat Politècnica de Catalunya (PhD Thesis).

Appendix B

Characterising Andorra's endosomatic and exosomatic metabolism dependence on externalised processes.

B.1. Externalisation calculation for Andorra.

B.1.1. The externalisation of energy.

B.1.1.1. Inputs and outputs of types of structural, metabolic processors.

The values characterising the different externalised processes come from the database Di Felice (2020), accessible through Zenodo. Table B1 summarises nexus inputs and outputs associated with externalised processes needed to produce energy carriers (i.e. electricity and oil products). Table B2 refers to externalised processes related to extracting primary energy sources (e.g. coal, oil, uranium) and intermediary steps (e.g. the production of the nuclear fuel element). These inputs and outputs are collected in a unitary description. Boundaries are set for the extracting energy sources required to produce imported energy carriers. This means that the water needed to extract oil used to produce imported fuels is accounted for, but we do not account for the inputs and outputs associated with using this water. Regarding the observable attributes:

1. For each data point on human activity, employment figures are converted into hours by assuming an average of 1800 working hours per year. Only direct employment (e.g., operation and maintenance of power plants) is considered.
2. Land use for primary energy source conversion processes, apart from wind turbines, solar panels, and hydropower, is negligible.
3. Water bio is the elementary flow resource or the water withdrawal. This selection means, for example, that the water flow input for hydropower plants represents the water passing through the dam and not only the water evaporated during the process.
4. Greenhouse gases are converted into their CO_2 equivalent using Global Warming Potentials (GWPs) over a 100-year horizon (GWP100) as reported by the Intergovernmental Panel on Climate Change (IPCC, 2007) and summed into a single output.

Table B1. Metabolic processors to produce energy carriers.

Processor name	***Observable attribute***	***Label***	***Value***	***Unit***
Nuclear plant	Human activity	Internal fund input	1.81E-05	hours
Nuclear plant	Land use	Internal fund input	n/a	hectares
Nuclear plant	Water bio	External flow input	2.05E+01	litres
Nuclear plant	Greenhouse gases	External flow output	n/a	$KgCO_2eq$
Nuclear plant	**Electricity**	**Useful output**	**1.00E+00**	**MJ**
Natural gas turbines	Human activity	Internal fund input	1.69E-05	hours
Natural gas turbines	Land use	Internal fund input	n/a	hectares
Natural gas turbines	Water bio	External flow input	1.47E+01	litres
Natural gas turbines	Greenhouse gases	External flow output	1.21E-01	$KgCO_2eq$
Natural gas turbine	**Electricity**	**Useful output**	**1.00E+00**	**MJ**
Coal power plant	Human activity	Internal fund input	3.60E-05	hours
Coal power plant	Land use	Internal fund input	n/a	hectares
Coal power plant	Water bio	External flow input	1.48E+01	litres
Coal power plant	Greenhouse gases	External flow output	2.67E-01	$KgCO_2eq$
Coal power plant	**Electricity**	**Useful output**	**1.00E+00**	**MJ**
Wind Turbines	Human activity	Internal fund input	3.10E-05	hours
Wind Turbines	Land use	Internal fund input	3.81E-08	hectares
Wind Turbines	Water bio	External flow input	n/a	litres
Wind Turbines	Greenhouse gases	External flow output	n/a	$KgCO_2eq$
Wind Turbines	**Electricity**	**Useful output**	**1.00E+00**	**MJ**
Solar PV	Human activity	Internal fund input	2.88E-04	hours
Solar PV	Land use	Internal fund input	3.78E-07	hectares
Solar PV	Water bio	External flow input	n/a	litres
Solar PV	Greenhouse gases	External flow output	n/a	$KgCO_2eq$
Solar PV	**Electricity**	**Useful output**	**1.00E+00**	**MJ**

Hydro	Human activity	Internal fund input	1.39E-05	hours
Hydro	Land use	Internal fund input	6.39E-09	hectares
Hydro	Water bio	External flow input	2.25E+03	litres
Hydro	Greenhouse gases	External flow output	n/a	KgCO_2eq
Hydro	**Electricity**	**Useful output**	**1.00E+00**	**MJ**
CHP	Human activity	Internal fund input	8.47E-05	hours
CHP	Land use	Internal fund input	n/a	hectares
CHP	Water bio	External flow input	3.79E+00	litres
CHP	Greenhouse gases	External flow output	1.20E-01	KgCO_2eq
CHP	**Electricity**	**Useful output**	**1.00E+00**	**MJ**
Hydroskimming refinery	Human activity	Internal fund input	2.28E-05	hours
Hydroskimming refinery	Land use	Internal fund input	n/a	hectares
Hydroskimming refinery	Water bio	External flow input	7.19E-03	litres
Hydroskimming refinery	Greenhouse gases	External flow output	2.84E-03	KgCO_2eq
Hydroskimming refinery	**Total oil products**	**Useful output**	**1.00E+00**	**MJ**
Medium conversion refinery	Human activity	Internal fund input	2.28E-05	hours
Medium conversion refinery	Land use	Internal fund input	n/a	hectares
Medium conversion refinery	Water bio	External flow input	7.19E-03	litres
Medium conversion refinery	Greenhouse gases	External flow output	5.18E-03	KgCO_2eq
Medium conversion refinery	**Total oil products**	**Useful output**	**1.00E+00**	**MJ**
Deep conversion with coking refinery	Human activity	Internal fund input	2.28E-05	hours
Deep conversion with coking refinery	Land use	Internal fund input	n/a	hectares
Deep conversion with coking refinery	Water bio	External flow input	1.00E-02	litres
Deep conversion with coking refinery	Greenhouse gases	External flow output	1.19E-02	KgCO_2eq
Deep conversion with coking refinery	**Total oil products**	**Useful output**	**1.00E+00**	**MJ**
Deep conversion with hydrocracking refinery	Human activity	Internal fund input	2.28E-05	hours
Deep conversion with hydrocracking refinery	Land use	Internal fund input	n/a	hectares

Deep conversion with hydrocracking refinery	Water bio	External flow input	7.19E-03	litres
Deep conversion with hydrocracking refinery	Greenhouse gases	External flow output	1.57E-02	KgCO$_2$eq
Deep conversion with hydrocracking refinery	**Total oil products**	**Useful output**	**1.00E+00**	**MJ**

Source: Di Felice (2020).

Table B2. Metabolic processors for the extraction of primary energy sources and intermediate steps.

Processor name	***Observable attribute***	***Label***	***Value***	***Unit***
Nuclear fuel plant	Human activity	Internal fund input	7.00E-02	hours
Nuclear fuel plant	Land use	Internal fund input	n/a	hectares
Nuclear fuel plant	Water bio	External flow input	9.00E+02	litres
Nuclear fuel plant	Greenhouse gases	External flow output	n/a	KgCO$_2$eq
Nuclear fuel plant	**Nuclear fuel element**	**Useful output**	**1.00E+00**	**kg**
Open-pit uranium mining	Human activity	Internal fund input	3.00E-01	hours
Open-pit uranium mining	Land use	Internal fund input	3.64E-05	hectares
Open-pit uranium mining	Water bio	External flow input	6.00E+03	litres
Open-pit uranium mining	Greenhouse gases	External flow output	n/a	KgCO$_2$eq
Open-pit uranium mining	**Uranium**	**Useful output**	**1.00E+00**	**kg**
In situ leaching uranium mining	Human activity	Internal fund input	9.00E-01	hours
In situ leaching uranium mining	Land use	Internal fund input	3.12E-06	hectares
In situ leaching uranium mining	Water bio	External flow input	n/a	litres
In situ leaching uranium mining	Greenhouse gases	External flow output	n/a	KgCO$_2$eq
In situ leaching uranium mining	**Uranium**	**Useful output**	**1.00E+00**	**kg**
Onshore gas extraction	Human activity	Internal fund input	1.28E-02	hours
Onshore gas extraction	Land use	Internal fund input	1.00E-08	hectares
Onshore gas extraction	Water bio	External flow input	2.55E-01	litres
Onshore gas extraction	Greenhouse gases	External flow output	1.30E-01	KgCO$_2$eq
Onshore gas extraction	**Gas**	**Useful output**	**1.00E+00**	**m^3**

Offshore gas extraction	Human activity	Internal fund input	1.28E-02	hours
Offshore gas extraction	Land use	Internal fund input	n/a	hectares
Offshore gas extraction	Water bio	External flow input	n/a	litres
Offshore gas extraction	Greenhouse gases	External flow output	9.00E-02	$KgCO_2eq$
Offshore gas extraction	**Gas**	**Useful output**	**1.00E+00**	**m^3**
Open-pit coal mining	Human activity	Internal fund input	2.40E-06	hours
Open-pit coal mining	Land use	Internal fund input	2.25E-08	hectares
Open-pit coal mining	Water bio	External flow input	9.50E-07	litres
Open-pit coal mining	Greenhouse gases	External flow output	1.24E-03	$KgCO_2eq$
Open-pit coal mining	**Coal**	**Useful output**	**1.00E+00**	**kg**
Underground coal mining	Human activity	Internal fund input	2.40E-03	hours
Underground coal mining	Land use	Internal fund input	2.06E-05	hectares
Underground coal mining	Water bio	External flow input	1.58E+00	litres
Underground coal mining	Greenhouse gases	External flow output	3.40E-01	$KgCO_2eq$
Underground coal mining	**Coal**	**Useful output**	**1.00E+00**	**kg**
Onshore light oil extraction	Human activity	Internal fund input	5.88E-04	hours
Onshore light oil extraction	Land use	Internal fund input	1.21E-06	hectares
Onshore light oil extraction	Water bio	External flow input	4.80E-01	litres
Onshore light oil extraction	Greenhouse gases	External flow output	3.06E-01	$KgCO_2eq$
Onshore light oil extraction	**Oil**	**Useful output**	**1.00E+00**	**kg**
Offshore light oil extraction	Human activity	Internal fund input	5.88E-04	hours
Offshore light oil extraction	Land use	Internal fund input	n/a	hectares
Offshore light oil extraction	Water bio	External flow input	5.39E-02	litres
Offshore light oil extraction	Greenhouse gases	External flow output	3.33E-01	$KgCO_2eq$
Offshore light oil extraction	**Oil**	**Useful output**	**1.00E+00**	**kg**
Onshore medium oil extraction	Human activity	Internal fund input	5.88E-04	hours
Onshore medium oil extraction	Land use	Internal fund input	1.21E-06	hectares

Onshore medium oil extraction	Water bio	External flow input	4.95E-01	litres
Onshore medium oil extraction	Greenhouse gases	External flow output	3.60E-01	KgCO_2eq
Onshore medium oil extraction	**Oil**	**Useful output**	**1.00E+00**	**kg**
Offshore medium oil extraction	Human activity	Internal fund input	5.88E-04	hours
Offshore medium oil extraction	Land use	Internal fund input	n/a	hectares
Offshore medium oil extraction	Water bio	External flow input	1.49E-01	litres
Offshore medium oil extraction	Greenhouse gases	External flow output	1.86E-01	KgCO_2eq
Offshore medium oil extraction	**Oil**	**Useful output**	**1.00E+00**	**kg**
Offshore heavy oil extraction	Human activity	Internal fund input	5.88E-04	hours
Offshore heavy oil extraction	Land use	Internal fund input	n/a	hectares
Offshore heavy oil extraction	Water bio	External flow input	1.29E+00	litres
Offshore heavy oil extraction	Greenhouse gases	External flow output	3.54E-01	KgCO_2eq
Offshore heavy oil extraction	**Oil**	**Useful output**	**1.00E+00**	**kg**

Source: Di Felice (2020).

B.1.1.2. Aggregation in extensive values.

Once the values in the unitary description are compiled, the second step is scaling each unitary processor onto contextualised, extensive representations. This requires the following information:

- Data on extensive outputs of imported energy commodities (i.e. how much electricity is imported from Spain and France and how much oil products are imported).
- Data on the extensive output of each externalised process depending on the structural mix (e.g. how much electricity imported from Spain comes from natural gas turbines and how much gas needed for electricity production is extracted offshore vs. how much is extracted onshore).

B.1.1.2.1. Electricity imported from Spain.

Imported electricity from Spain in 2019 amounted to 201 GWh. The electricity generation mix in Spain is shown in Table B3, using the information collected in REE (2020) and discounting the values below 4%.

Table B3. Structural mix to produce electricity in Spain.

Structural type	***Percentage***
Nuclear Plant	24%
Natural gas turbine	22%
Coal power plant	4%
Wind Turbine	23%
Solar PV	4%
Hydro	11%
CHP	12%

Source: Own elaboration from REE (2020).

In turn, it is necessary to know the structural mix of processes related to extraction activities and intermediate processes. This information is available in Di Felice (2020), considering global averages. Table B4 shows the values contemplated.

Table B4. Structural mix considered for extraction processes.

Structural type	***Percentage***
Nuclear fuel plant	100%
Open-pit uranium mining	70%
In situ leaching uranium mining	30%
Onshore gas extraction	67%
Offshore gas extraction	33%
Open-pit coal mining	80%
Underground coal mining	20%

Source: Di Felice (2020).

Table B5 shows the calculated values of primary energy sources and intermediate inputs of the electricity imported from Spain. These values are hidden in official statistics based on the accounting of energy carriers. Finally, Table B6 shows the nexus input and outputs associated with the imported electricity from Spain.

Table B5. Primary energy sources and intermediated inputs related to the electricity imported from Spain.

Name	***Amount***	***Unit***
Nuclear fuel element	119	kg
Uranium	112	kg
Gas	14 089 792	m^3
Coal	3 417 273	kg

Source: Own elaboration from Di Felice (2020).

Table B6. Nexus inputs and outputs associated with the electricity imported from Spain.

Observable attribute	***Electricity production***	***Extraction of primary energy sources***	***Total externalised processes electricity from Spain***
Human activity (hours)	28 831	182 058	210 889
Land use (hectares)	18	14	32
Water abstraction (m^3)	185 748 699	4 065	185 752 764
GHG emissions ($kgCO_2eq$)	37 410 120	1 881 452	39 291 572

Source: Own elaboration.

B.1.1.2.2. Electricity imported from France.

Imported electricity from France during the year 2019 amounts to 255 GWh. The mix of electricity generation in France is shown in Table B7, using the information collected in RTE (2019) and discounting the values below 4%.

Table B7. Structural mix to produce electricity in France.

Structural type	***Percentage***
Nuclear Plant	74%
Natural gas turbine	8%

Wind Turbine	6%
Hydro	12%

Source: Own elaboration from RTE (2019).

Table B4 lists the structural mix of processes related to extraction activities and intermediate processes. Table B8 shows the calculated values of primary energy sources and intermediate inputs of the electricity imported from France. Finally, Table B9 offers the nexus inputs and outputs associated with the imported electricity from France.

Table B8. Primary energy sources and intermediated inputs related to the electricity imported from France.

Name	***Amount***	***Unit***
Nuclear fuel element	464	kg
Uranium	438	kg
Gas	4 046 544	m^3

Source: Own elaboration from Di Felice (2020).

Table B9. Nexus inputs and outputs associated with the electricity imported from France.

Observable attribute	***Electricity production***	***Extraction of primary energy sources***	***Total externalised processes electricity from France***
Human activity (hours)	16 749	52 039	68 787
Land use (hectares)	3	0.04	3.04
Water abstraction (m^3)	262 865 628	2 950	262 868 578
GHG emissions ($kgCO_2eq$)	8 886 240	472 636	9 358 876

Source: Own elaboration.

B.1.1.2.3. Oil products.

According to Miquel et al. (2021), the total petroleum products imported (considered Spain the leading exporter) amounts to 158.004 TEP. The structural mix of refinery processes in Spain is shown in Table B10, and the average global combination of oil extraction processes is in Table B11 (Di Felice, 2020).

Table B10. The structural mix of refinery processes in Spain.

Structural type	***Percentage***
Hydroskimming refinery	6%
Medium conversion refinery	30%
Deep conversion with coking refinery	29%
Deep conversion with hydrocracking refinery	35%

Source: Di Felice (2020).

Table B11. A global average of oil extraction processes.

Structural type	***Percentage***
Onshore light oil extraction	49%
Offshore light oil extraction	15%
Onshore medium oil extraction	27%
Offshore medium oil extraction	8%
Offshore heavy oil extraction	1%

Source: Di Felice (2020).

The set of petroleum products requires an estimated oil extraction of 150 167 570 kg. Table B12 summarises the nexus inputs and outputs associated with the imported oil products.

Table B12. Nexus inputs and outputs associated with the imported oil products.

Observable attribute	***Refining***	***Oil extraction***	***Total externalised processes related to imported oil products***
Human activity (hours)	150 598	88 299	238 897
Land use (hectares)	n/a	138	138
Water abstraction (m^3)	52 955	60 521	113 476
GHG emissions ($kgCO_2eq$)	70 587 970	47 307 835	117 895 806

Source: Own elaboration.

B.1.2. The externalisation of food.

B.1.2.1. Vegetables.

B.1.2.1.1. Inputs of types of structural, metabolic processors.

The values characterising the different externalised processes come from the database Cadillo-Benalcazar and Renner (2020), accessible through Zenodo. Table B13 summarises nexus inputs and outputs associated with externalised processes needed to produce the imported plant-based food commodities. The technical coefficients used are those of Spain, the leading exporter to Andorra (Andorran Government, 2020). Numbers are expressed in unitary description (i.e. the production of a ton of crop was used as a reference unit). Concerning the observable attributes:

1. Land is intended as the area devoted to crop production.
2. Bluewater is considered to be the fraction of water distributed for irrigation.
3. Human activity is the working hours of the processor.

Table B13. Plant-based food metabolic processors.

Group	***Processor name***	***Observable attribute***	***Label***	***Value***	***Unit***
Roots and Tubers and Derived Products	Potatoes	Land	Internal fund input	0.032852914	Hectares
	Potatoes	Bluewater	External flow input	76.83361642	m^3
	Potatoes	Human activity	Internal fund input	4.188650898	Hours
	Potatoes	**Potatoes and products**	**Useful output**	**1**	**Tonne**
Vegetables and Derived Products	Onions, dry	Land	Internal fund input	0.019549119	Hectares
	Onions, dry	Bluewater	External flow input	32.7879849	m^3
	Onions, dry	Human activity	Internal fund input	7.526311881	Hours
	Onions, dry	**Onions**	**Useful output**	**1**	**Tonne**
Vegetables and Derived Products	Tomatoes, fresh	Land	Internal fund input	0.01201067	Hectares
	Tomatoes, fresh	Bluewater	External flow input	22.75920964	m^3
	Tomatoes, fresh	Human activity	Internal fund input	4.624047247	Hours
	Tomatoes, fresh	**Tomatoes and products**	**Useful output**	**1**	**Tonne**
	Vegetables, fresh nes	Land	Internal fund input	0.047912913	hectares

Vegetables and Derived Products	Vegetables, fresh nes	Bluewater	External flow input	32.7879849	m^3
	Vegetables, Fresh nes	Human activity	Internal fund input	18.44622911	Hours
	Vegetables, fresh nes	**Vegetables, other**	**Useful output**	**1**	**Tonne**
Pulses and Derived Products	Beans, dry	Land	Internal fund input	0.657289339	Hectares
	Beans, dry	Bluewater	External flow input	215.0874864	m^3
	Beans, dry	Human activity	Internal fund input	9.637284823	Hours
	Beans, dry	**Beans**	**Useful output**	**1**	**Tonne**
Pulses and Derived Products	Peas, dry	Land	Internal fund input	1.268230818	Hectares
	Peas, dry	Bluewater	External flow input	93.0721675	m^3
	Peas, dry	Human activity	Internal fund input	18.59500968	Hours
	Peas, dry	**Peas**	**Useful output**	**1**	**Tonne**
Pulses and Derived Products	Pulses, nes	Land	Internal fund input	0.825354903	Hectares
	Pulses, nes	Bluewater	External flow input	228.0386641	m^3
	Pulses, nes	Human activity	Internal fund input	12.10148987	Hours
	Pulses, nes	**Pulses, other and products**	**Useful output**	**1**	**Tonne**
Nuts and Derived Products	Nuts, nes	Land	Internal fund input	0.4	Hectares
	Nuts, nes	Bluewater	External flow input	786.5469542	m^3
	Nuts, nes	Human activity	Internal fund input	36.19272178	Hours
	Nuts, nes	**Nuts and products**	**Useful output**	**1**	**Tonne**
Fruits and Derived Products	Bananas	Land	Internal fund input	0.024686786	Hectares
	Bananas	Bluewater	External flow input	133.2044756	m^3
	Bananas	Human activity	Internal fund input	9.000612682	Hours
	Bananas	**Bananas**	**Useful output**	**1**	**Tonne**
Fruits and Derived Products	Dates	Land	Internal fund input	0.154330514	Hectares
	Dates	Bluewater	External flow input	n/a	m^3
	Dates	Human activity	Internal fund input	56.26771996	Hours
	Dates	**Dates**	**Useful output**	**1**	**tonne**

Fruits and Derived Products	Pineapples	Land	Internal fund input	0.04787644	Hectares
	Pineapples	Bluewater	External flow input	9.662261676	m^3
	Pineapples	Human activity	Internal fund input	45.00664251	Hours
	Pineapples	**Pineapples and products**	**Useful output**	**1**	**Tonne**
Fruits and Derived Products	Oranges	Land	Internal fund input	0.051776182	Hectares
	Oranges	Bluewater	External flow input	159.7559711	m^3
	Oranges	Human activity	Internal fund input	18.8771982	Hours
	Oranges	**Oranges, mandarins**	**Useful output**	**1**	**Tonne**
Fruits and Derived Products	Grapes	Land	Internal fund input	0.177619893	Hectares
	Grapes	Bluewater	External flow input	133.9682157	m^3
	Grapes	Human activity	Internal fund input	64.75884871	Hours
	Grapes	**Grapes and products (excl wine)**	**Useful output**	**1**	**Tonne**
Fruits and Derived Products	Apples	Land	Internal fund input	0.06390593	Hectares
	Apples	Bluewater	External flow input	195.7638038	m^3
	Apples	Human activity	Internal fund input	23.29961134	Hours
	Apples	**Apples and products**	**Useful output**	**1**	**Tonne**
Fruits and Derived Products	Fruit, fresh nes	Land	Internal fund input	0.110256014	Hectares
	Fruit, fresh nes	Bluewater	External flow input	417.8602221	m^3
	Fruit, fresh nes	Human activity	Internal fund input	40.19849591	Hours
	Fruit, fresh nes	**Fruits, other**	**Useful output**	**1**	**Tonne**
Spices	Spices nes	Land	Internal fund input	1	Hectares
	Spices nes	Bluewater	External flow input	2972.052724	m^3
	Spices nes	Human activity	Internal fund input	384.9589498	Hours
	Spices nes	**Spices, other**	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Barley	Land	Internal fund input	0.451814033	Hectares
	Barley	Bluewater	External flow input	83.69023075	m^3
	Barley	Human activity	Internal fund input	12.23310782	hours

	Barley	**Barley and products**	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Cereals, nes	Land	Internal fund input	1.051303616	Hectares
	Cereals, nes	Bluewater	External flow input	604.8446034	m^3
	Cereals, nes	Human activity	Internal fund input	28.46461053	Hours
	Cereals, nes	Cereals, other	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Maize	Land	Internal fund input	0.091605291	Hectares
	Maize	Bluewater	External flow input	405.6711844	m^3
	Maize	Human activity	Internal fund input	2.480262498	Hours
	Maize	**Maize and products**	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Oats	Land	Internal fund input	0.641848524	Hectares
	Oats	Bluewater	External flow input	1281.833922	m^3
	Oats	Human activity	Internal fund input	17.3783938	Hours
	Oats	**Oats**	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Rice, paddy	Land	Internal fund input	0.125409147	Hectares
	Rice, paddy	Bluewater	External flow input	1205.426718	m^3
	Rice, paddy	Human activity	Internal fund input	3.395520076	Hours
	Rice, paddy	**Rice (milled equivalent)**	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Rye	Land	Internal fund input	0.63000063	Hectares
	Rye	Bluewater	External flow input	604.8446034	m^3
	Rye	Human activity	Internal fund input	17.0576057	Hours
	Rye	**Rye and products**	**Useful output**	**1**	**Tonne**
Cereals and cereal products	Wheat	Land	Internal fund input	0.42162071	Hectares
	Wheat	Bluewater	External flow input	47.6009617	m^3
	Wheat	Human activity	Internal fund input	11.41560736	Hours
	Wheat	**Wheat and products**	**Useful output**	**1**	**Tonne**
Oil-Bearing Crops and Derived Products	Soybeans	Land	Internal fund input	0.360841482	Hectares
	Soybeans	Bluewater	External flow input	2624.352883	m^3

	Soybeans	Human activity	Internal fund input	17.73837299	Hours
	Soybeans	**Soybeans**	**Useful output**	**1**	**Tonne**
Oil-Bearing Crops and Derived Products	Sunflower seed	Land	Internal fund input	1.172882946	Hectares
	Sunflower seed	Bluewater	External flow input	902.8321434	m^3
	Sunflower seed	Human activity	Internal fund input	57.65699399	Hours
	Sunflower seed	**Sunflower seed**	**Useful output**	**1**	**Tonne**
Oil-Bearing Crops and Derived Products	Oilseeds nes	Land	Internal fund input	0.627730628	Hectares
	Oilseeds nes	Bluewater	External flow input	1199.236854	m^3
	Oilseeds nes	Human activity	Internal fund input	30.85820386	Hours
	Oilseeds nes	**Oilcrops, other**	**Useful output**	**1**	**Tonne**
Sugar Crops, Sweeteners and Derived Products	Sugar beet	Land	Internal fund input	0.011257053	Hectares
	Sugar beet	Bluewater	External flow input	56.41397948	m^3
	Sugar beet	Human activity	Internal fund input	0.75141833	Hours
	Sugar beet	**Sugar beet**	**Useful output**	**1**	**Tonne**

Source: Cadillo-Benalcazar and Renner (2020).

B.1.2.1.2. Aggregation in extensive values.

The selection of food commodities for quantification represents an undeniable epistemological challenge, given the wide variety of categories. Thus, only values above one tonne have been considered from food import data provided by the Customs Service of Andorra for the reference year 2019. Second, only primary or direct processed products (e.g. wheat and wheat flour) have been selected for quantification. Prepared foods considered relevant in the diet of the Andorran population and highlighted in the ENA survey (Govern d'Andorra, 2007), such as food paste and bakery products, have also been included in the analysis. Third, no alcoholic beverages have been counted due to the unavailability of extraction ratios. This choice can be significant for Andorra since imports associated with alcoholic drinks amount to 17 863 tonnes. However, it is generally difficult to track the raw materials used for alcoholic beverages. Finally, in the case of processed products, it is necessary to apply a processing coefficient which determines the quantity of the primary product that goes to the metabolic processor (e.g. frozen potatoes must be transformed into potatoes by multiplying 1.72 or wheat flour must be transformed into wheat by multiplying 1.35). The conversion factors of derived products to primary products are from (FAO, 2017a). Table B14 shows the Combined Nomenclature (CN) categories selected for the analysis, the aggregation into the different Food Commodity List (FCL) groups and the quantities of primary product estimated assigned to the various metabolic processors to calculate final biophysical requirements. The total primary plant-based products considered amount to 44 802 tonnes.

Table B14. Categories of plant-based food commodities selected for the analysis.

CN category	***FCL group***	***Primary product in processors (tonnes)***
07011000, 07019050, 07019090, 07101000, 11052000, 20041010, 20041099	Roots and Tubers and Derived Products	2 450
07020000, 07031019, 07099100, 07099390, 07099990, 07108080, 07108085, 07108095, 07109000, 07129090, 20021010, 20021090, 20029011, 20029019, 20029031, 07108059, 20011000, 20019097, 20029039, 20029099, 20049091, 20049098, 20051000, 20059930, 20059950, 20059980	Vegetables and Derived Products	12 667
07082000, 07102100, 07102200, 07134000, 07139000, 20054000, 20055100, 20055900	Pulses and Derived products	254
08023200, 08024100, 08029085,	Nuts and Derived products	28
08039010, 08039090, 08041000, 08042090, 08043000, 08051022, 08051028, 08051080, 08052110, 08052190, 08052200, 08061090, 08071100, 08071900, 08081080, 08083090, 08092900, 08093010, 08093090, 08101000, 08105000, 08109075, 08112090, 08119095, 08134095, 08135099, 20091199, 20091200, 20097120, 20097199, 20098969, 20098979, 20098999, 20099039, 20099051, 20099059, 20099098	Fruits and Derived products	6 951
09042200, 9096100, 09109999	Spices	64

10019120, 10019900, 10029000, 10039000, 10049000, 10051090, 10059000, 10061030, 10061079, 10062017, 10062092, 10062094, 10062098, 10063023, 10063061, 10063063, 10063065, 10063067, 10063092, 10063094, 10063096, 10063098, 10085000, 10089000, 11010011, 11010015, 11010090, 11022090, 11029070, 11029090, 11031110, 11031390, 11041910, 11063090, 11081990, 19021100, 19021910, 19021990, 19022010, 19022030, 19022091, 19022099, 19023010, 19023090, 19024010, 19024090, 19041090, 19042099, 19049010, 19049080, 19054090, 19059030, 19059070, 19059080	Cereals and Cereals products	6 770
12079996, 12089000, 12141000, 15091010, 15091020, 15091080, 15099000, 15100090, 15119099, 15121990, 15159099, 15162096, 15162098, 15171090, 15179091, 15179099	Oil-Bearing Crops and Derived Products	7 872
17011490, 17019100, 17019910, 17019990	Sugar Crops, Sweeteners and Derived Products	7 747

Source: Own elaboration from food import data provided by the Customs Service of Andorra and FAO (2017a).

Applying the metabolic processors and knowing the total amount imported for each group of vegetables, we can obtain the biophysical requirements per tonne shown in Table B15.

Table B15. Biophysical requirements per tonne for the different FCL groups.

FCL group	***Land (ha/tonne)***	***Bluewater (m^3/tonne)***	***Human activity (hours/tonne)***
Roots and Tubers and Derived Products	0.03	76.83	4.19
Vegetables and Derived Products	0.05	32.64	18.21
Pulses and Derived products	0.80	271.77	11.66
Nuts and Derived products	0.40	786.55	36.19
Fruits and Derived products	0.11	395.28	38.34
Spices	1.00	2972.05	384.96

Cereals and Cereals products	0.43	152.74	11.70
Oil-Bearing Crops and Derived Products	0.78	1120.21	38.10
Sugar Crops, Sweeteners and Derived Products	0.01	56.41	0.75

Source: Own elaboration.

Finally, Table B16 summarises the nexus inputs associated with the imported vegetables.

Table B16. Biophysical requirements for imported vegetables.

Observable attribute	***Total externalised to produce imported vegetables***	***Values per tonne of imported vegetables***
Human activity (hours)	920 888	20.55
Land use (hectares)	10 801	0.24
Bluewater (m^3)	13 904 792	310.36

Source: Own elaboration.

B.1.2.2. Meat.

B.1.2.2.1. Inputs of types of structural, metabolic processors.

To quantify requirements, assumptions must be made about the different types of animal production systems in Spain, the leading importing country. Table B17 shows the percentages considered for the various animal production systems based on information from Cadillo-Benalcazar and Renner (2020). Definitions for the different production systems can be found in FAO (2017b).

Table B17. Types of animal production systems for Spain.

Product	***Farm type***	***Percentage***
Pig meat	Industrial	100%
Chicken meat	Layers	8%
	Broilers	92%

Bovine meat	Grassland/dairy	17%
	Mixed/dairy	17%
	Grassland/non-dairy	33%
	Mixed/non-dairy	33%
Mutton & goat meat	Grassland/dairy	9%
	Mixed/dairy	28%
	Grassland/non-dairy	15%
	Mixed/non-dairy	48%

Source: Cadillo-Benalcazar and Renner (2020).

After considering the different animal production systems, selecting the animal metabolic processors associated with producing the different types of imported meat is possible. Table B18 summarises the values considered taken from Cadillo-Benalcazar and Renner (2020) where:

1. Bluewater is service water and water consumption for animals.
2. Human activity is working hours by processor.
3. Feed is the feed consumed by type of animal and production system.

Table B18. Animal processors for each animal production system.

Animal Production System	***Processor name***	***Observable attribute***	***Label***	***Value***	***Unit***
Industrial	Pigs	Bluewater	External flow input	153.5074953	m^3
	Pigs	Human activity	Internal fund input	107.3677854	hours
	Pigs	Feed	Internal flow input	3.82887761	tonne
	Pigs	**Pig meat**	**Useful output**	**1**	**tonne**
Layers	Chickens	Bluewater	External flow input	15.50738539	m^3
	Chickens	Human activity	Internal fund input	46.59647033	hours
	Chickens	Feed	Internal flow input	21.00603351	tonne
	Chickens	**Chicken meat**	**Useful output**	**1**	**tonne**

Broilers	Chickens	Bluewater	External flow input	10.94675915	m^3
	Chickens	Human activity	Internal fund input	8.223184065	hours
	Chickens	Feed	Internal flow input	3.676033377	tonne
	Chickens	**Chicken meat**	**Useful output**	**1**	**tonne**
Grassland/dairy	Cattle	Bluewater	External flow input	163.287238	m^3
	Cattle	Human activity	Internal fund input	458.1627018	hours
	Cattle	Feed	Internal flow input	39.60064878	tonne
	Cattle	**Bovine meat**	**Useful output**	**1**	**tonne**
Mixed/dairy	Cattle	Bluewater	External flow input	238.6367762	m^3
	Cattle	Human activity	Internal fund input	439.8724919	hours
	Cattle	Feed	Internal flow input	39.60065463	tonne
	Cattle	**Bovine meat**	**Useful output**	**1**	**tonne**
Grassland/non-dairy	Cattle	Bluewater	External flow input	92.39406897	m^3
	Cattle	Human activity	Internal fund input	229.9605565	hours
	Cattle	Feed	Internal flow input	24.92620645	tonne
	Cattle	**Bovine meat**	**Useful output**	**1**	**tonne**
Mixed/non-dairy	Cattle	Bluewater	External flow input	122.3862731	m^3
	Cattle	Human activity	Internal fund input	217.7054615	hours
	Cattle	Feed	Internal flow input	24.92621011	tonne
	Cattle	**Bovine meat**	**Useful output**	**1**	**tonne**
Grassland/dairy	Sheep	Bluewater	External flow input	174.5572308	m^3
	Sheep	Human activity	Internal fund input	182.8025324	hours
	Sheep	Feed	Internal flow input	21.75614797	tonne
	Sheep	**Mutton & goat meat**	**Useful output**	**1**	**tonne**
Mixed/dairy	Sheep	Bluewater	External flow input	174.5572396	m^3
	Sheep	Human activity	Internal fund input	182.8025416	hours
	Sheep	Feed	Internal flow input	21.75614997	tonne

	Sheep	**Mutton & goat meat**	**Useful output**	**1**	**tonne**
Grassland/non-dairy	Sheep	Bluewater	External flow input	174.5572577	m^3
	Sheep	Human activity	Internal fund input	182.8025606	hours
	Sheep	Feed	Internal flow input	20.01802708	tonne
	Sheep	**Mutton & goat meat**	**Useful output**	**1**	**tonne**
Mixed/non-dairy	Sheep	Bluewater	External flow input	174.5572577	m^3
	Sheep	Human activity	Internal fund input	182.8025606	hours
	Sheep	Feed	Internal flow input	20.01802708	tonne
	Sheep	**Mutton & goat meat**	**Useful output**	**1**	**tonne**

Source: Cadillo-Benalcazar and Renner (2020).

B.1.2.2.2. Aggregation in extensive values.

Accounting for biophysical requirements for imported meat also requires different assumptions. As for vegetables, only the categories of imported meat exceeding the tonne have been considered. Moreover, sausages and edible offal are not considered. Eggs and milk have been considered by-products to avoid double accounting (e.g. layers production systems produce eggs and meat, and grassland/dairy production systems produce meat and milk). Table B19 shows the Combined Nomenclature (CN) categories selected for the analysis, the aggregation into the different animal-based food commodities (i.e. the different types of meat) and the quantities of primary product estimated assigned to the various metabolic processors to calculate the final biophysical requirements. The total primary product considered amounted to **5 403** tonnes.

Table B19. Categories of animal-based food commodities selected for the analysis.

CN category	***Type of meat***	***Primary product in processors (tonnes)***
02031110, 02031211, 02031219, 02031913, 02031915, 02031955, 02031959, 02032110, 02032955, 02032959, 02032990, 02091011, 02091019, 02101131, 02101139, 02101190, 02101211, 02101219, 02101290, 02101950, 02101981, 02101989, 02101990	Pig meat	1 911
02071110, 02071130, 02071190, 02071290, 02071310, 02071320, 02071330, 02071350, 02071360, 02071370, 02071410, 02071420, 02071430, 02071450, 02071460,	Chicken meat	1 659

02071470, 02072410, 02072610, 02072680, 02072710, 02072780		
02011000, 02012020, 02012030, 0201205, 02012090, 02013000, 02022030, 02022090, 02023050, 02023090, 02102090	Bovine meat	1 624
02041000, 02042100, 02042210, 02042290, 02044210, 02044290, 02045011, 02045031, 02045071	Mutton & goat meat	209

Source: Own elaboration from food import data provided by the Customs Service of Andorra.

Finally, Table B20 summarises the nexus inputs associated with the imported meat (without considering feed requirements).

Table B20. Biophysical requirements for imported meat.

Observable attribute	***Total externalised to produce imported meat***	***Values per tonne of imported meat***
Human activity (hours)	749 306	139
Bluewater (m^3)	573 985	106
Feed (tonnes)	68 570	13

Source: Own elaboration using Cadillo-Benalcazar and Renner (2020).

B.1.2.2.3. Emissions from livestock.

Cadillo-Benalcazar and Renner's (2020) processors do not have information on greenhouse gas emissions linked to the production of plant-based and animal-based food commodities. However, the database does have information on the stock of animals attached to the production of one tonne of meat that I have used to estimate methane emissions related to enteric fermentation and manure management, amounting to **37 817 927** kg of CO_2eq. Table B21 summarises the information used and the results obtained.

Table B21. Accounting of GHG emissions concerning enteric fermentation and manure management to produce meat.

Type of meat	Animal Type	CH4 emissions enteric fermentation (IPCC, 2006) (kg per capita and year)	CH4 emissions manure management (IPCC, 2006) (kg per capita and year)	Stock of heads per year related to imported meat	Total kg CO2eq (AR5)
Pig meat	Adult females	n.a	6	13 172	2.212.947
	Adult males	n.a	6		
	Replacement females	n.a	6		
	Replacement males	n.a	6		
	All fattening	n.a	6		
Chicken Meat	Adult females	n.a	0.03	190 401	159.936
	Adult males	n.a	0.03		
	Replacement females	n.a	0.03		
	Replacement males	n.a	0.03		
	All fattening	n.a	0.03		
Bovine meat	Adult females	73	6	16 257	32.307.367
	Adult males	66	6		
	Replacement females	35	6		
	Replacement males	35	6		
	Fattening females	73	6		
	Fattening males	66	6		
Mutton & goat meat	Adult females	8	0.19	13 683	3.137.676
	Adult males	8	0.19		
	Replacement females	8	0.19		
	Replacement males	8	0.19		
	Fattening females	8	0.19		
	Fattening males	8	0.19		

Source: Own elaboration using Cadillo-Benalcazar and Renner (2020) and IPCC (2006).

B.1.2.2.4. Feed.

Given the number of feed types, quantifying biophysical requirements associated with feed consumption has posed an epistemological challenge. Efforts have been made to avoid double-counting, for example, by looking at soya eaten by animals and soya byproducts such as flour and soya cake as if the latter needed new soya inputs to be produced. Ultimately, we have considered the 100% inputs in the categories “swill & roughages” and “grains & food crops” from Cadillo-Benalcazar and Renner (2020). We have also considered “agro-industrial byproducts,” which have a higher percentage of 50% concerning the primary product. For example, the “cake of soybeans” has a primary product percentage of 0.8, while “molasses” has a rate of 0.13. Only the first has been taken into consideration, not the second. In addition, we have assumed that the total quantity of agro-industrial byproducts is divided proportionally by those that exceed 50% concerning the primary product. For example, in most cases, 50% of agro-industrial products are constituted by “cake of rapeseed” and the other 50% by “cake of soybeans”. Finally, it is essential to note that given a specific amount of agro-industrial by-products, this must be transformed into the dry primary product (applying a multiplier). Then, this last quantity must be converted into wet matter (using another multiplier) to obtain the final input that goes to the processor. For example, the “cake of soybeans” is multiplied by 1.25 to get the quantity of dry soybeans. This quantity is, in turn, multiplied by 1.10 to obtain the input of the processor “soybeans”. Details are in Cadillo-Benalcazar and Renner (2020). Table B22 synthesises the results.

Table B22. Inputs requirements associated with feed.

Product	***Land (ha)***	***Bluewater (cubic meters)***	***Human activity (hours)***
Feed to pig meat	2 597	12 432 230	107 589
Feed to chicken meat	3 078	9 027 504	106 512
Feed to bovine meat	13 173	6 911 761	254 145
Feed to mutton and goat meat	1 413	1 916 167	46 045

Source: Own elaboration using Cadillo-Benalcazar and Renner (2020).

So, total feed requirements amount to **20 261** ha of land, **30 287 662** cubic meters of water and **514 291** hours of human activity.

Considering the values above, Table B23 expresses the nexus inputs associated with the imported meat (**5 403 tonnes**), also considering feed requirements.

Table B23. Biophysical requirements for imported meat.

Observable attribute	***Total externalised to produce imported meat***	***Values per tonne of imported meat***
Human activity (hours)	1 263 597	234
Bluewater (m^3)	30 861 647	5 712
Land (hectares)	20 261	4

Source: Own elaboration.

B.2. Nexus values characterising the local production in the energy and food sectors of Andorra.

Nexus values characterising the local production in the energy and food sectors of Andorra are of vital importance. These represent the basis for comparing the virtual values calculated for the externalised processes. Regarding this work, the values considered are the following:

- *Human activity*: Employment figures are converted into hours by assuming an average of 1 800 working hours per year. As only direct employment is considered (e.g. operation and maintenance of power plants), of the 172 workers listed in the Andorran Government (2020) linked to the production and distribution of energy, gas and water, only a quarter have been considered to be workers whose function is the production of energy itself. The resulting value is 77 400 hours. As regards the agricultural sector, given the close interrelationship between the different activities in the sector (e.g. tobacco production, livestock care, pasture land preparation, etc.), the total number of employees belonging to the heading of agriculture and livestock (Andorran Government, 2020) has been considered, amounting to a total of 160 workers and 288 000 hours.
- *Land Use*: For the energy sector, reliable values were unavailable for Andorra. Therefore, a calculated reference value has been applied based on Di Felice (2020). For this purpose, the different electricity production processes in Andorra have been considered. The corresponding extension of land use has been calculated according to the quantity of electricity (resulting from evaluating the Andorran structural mix) assigned to the metabolic processors hydro (75%), waste (18%) and solar (1%) found in Miquel et al. (2021). The resulting

benchmark is 4.38 hectares. In the agricultural sector, the value of the total cultivated area (Agricultural Department, 2019) has been selected, amounting to 2 077 hectares.

- *Water*: For the energy sector, the values for water abstraction correspond to the data provided in the report of the Andorran Government (2021) on water consumption to produce hydroelectric power (70 530 048 cubic meters/year), the Comella waste plant (4 067 cubic meters/year) and a reference value of 527 925 (cubic meters/year) from Di Felice (2020) for combined cycle plants. The total value amounts to 71 062 580 cubic meters for 2019. As regards the agricultural sector, the values considered are water for irrigation (1 950 000 cubic meters) and water for livestock consumption (93 871 cubic meters), both in Andorran Government (2021).
- *Emissions*: Emissions for the energy sector come from Miquel et al. (2021). Emissions to produce electricity (from waste) amount to 5.62 Gg CO_2eq, and emissions for making electricity and heat (CHP) amount to 4.19 Gg CO2eq. In turn, emissions in the agricultural sector are also in the same report. Only methane emissions from enteric fermentation (4.75 Gg CO2eq) and manure management (0.87 Gg CO2eq) have been considered.

B.3. Diagnosis calculation for Andorra.

To perform the calculations should be taken into account the following:

1. *Human Activity.*

1.1. Total Human Activity (THA) (level N): To know this value, it is first necessary to calculate the equivalent population (EP) from Equation A1 using data from the Department of Statistics (2019). To convert the value of the population equivalent to hours of human activity, we must multiply by 8 760.

1.2. Paid work (PW) (levels N-1 and N-2): Data on workers for the various economic activities come from the Department of Statistics (2019). Consider that direct and indirect employment, as well as an estimate of extra hours from CRES (2018), are included in this category. To convert the value of workers to working hours, we must multiply by 1 800, which is the maximum annual working hours in Andorra.

1.3. Other users (level N-1): This category includes the hours of the frontier workers, plus the hours of hikers and nights spent by tourists, except for 16% of these hours, which are considered to be tourists staying in private residences according to information in Department of Statistics (2019).

1.4. Household (level N-1): This category is calculated by the difference between the hours of THA minus the hours of PW and other users.

2. *Economic variables.*

Data on economic variables are sourced from the Department of Statistics (2019).

3. Energy.

Data on total energy consumption is sourced from Miquel et al. (2021). The electricity values for the different functional compartments are sourced from the Department of Statistics (2019). Percentages for heat and fuel are taken from Travesset-Baro (2017).

4. Food.

Data on gross food supply belong to Andorra government (2007), assuming an average daily intake of 1 854 kcal.

References

Agricultural Department, 2019. Agricultural and livestock statistics [WWW Document]. https://www.agricultura.ad/estadistiques (accessed 25 March 2023)

Andorran Government, 2021. Estudi per a l'elaboració anyal de l'inventari i la quantificació de la despesa hídrica per usos del principat d'Andorra - Any 2019. Govern d'Andorra, Andorra la Vella.

Andorran Government, 2020. Andorra en xifres 2020. Govern d'Andorra, Andorra la Vella.

Andorran Government, 2007. Avaluació de l'estat nutricional de la població d'Andorra 2004-2005. Govern d'Andorra, Andorra la Vella.

Cadillo-Benalcazar, J.J., Renner, A., 2020. Top-down and bottom-up vegetal and animal product metabolic profiles for 29 European countries (EU27 + United Kingdom + Norway) [dataset] [WWW Document]. Zenodo. https://doi.org/10.5281/ZENODO.3923010 (accessed 10 February 2022)

CRES, 2018. Estudi sobre el mercat de treball d'Andorra. Centre de Recerca Sociològica, Andorra la Vella.

Department of Statistics, 2019. Demographic, social and economic statistics [WWW Document]. https://www.estadistica.ad/portal/apps/sites/#/estadistica-en (accessed 6 June 2023)

Di Felice, L.J., 2020. Energy systems as holarchies: Complexity and sustainability across scales [dataset] [WWW Document]. Zenodo. URL https://doi.org/http://doi.org/10.5281/zenodo.4271325 (accessed 10 February 2022)

FAO, 2017a. Technical Conversion Factors for Agricultural Commodities.

FAO, 2017b. Global Livestock Environmental Assessment Model Description. Version 2.0. Rome.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group

I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Miquel, C., Cuyàs, M., Boneta, A., 2021. Cuarto informe bianual de actualización de Andorra ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Govern d’Andorra, Andorra la Vella.

Red Eléctrica de España (REE), 2020. El sistema eléctrico español 2019. Madrid.

Réseau de Transport d’Électricite (RTE), 2019. Bilan Électrique 2019. Paris.

Travesset-Baro, O., 2017. Prospectiva energètica al Principat d’Andorra. Model integrat d’avaluació de la seguretat energètica per a la transició cap a un escenari sostenibilista. Universitat Politècnica de Catalunya (PhD Thesis).

Appendix C

Libro de Actas XVII Jornadas de Economía Crítica Emergencias, Transiciones y Desigualdades Socioeconómicas

MuSIASEM: una metodología para el estudio de las bases biofísicas de los sistemas socioeconómicos desde la complejidad

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Resumen:

Los principales retos a los que se enfrenta la humanidad en el siglo XXI, entre los que se encuentran el cambio climático, la transición hacia un sistema energético basado en renovables o la pérdida de la biodiversidad, son biofísicos. Asimismo, las iniciativas que se han articulado para dar respuesta a estas emergencias, recogidas en los Objetivos del Desarrollo Sostenible (ODS), necesitan de la integración de información procedentede diferentes dimensiones (la biofísica, la económica, la social) y escalas de análisis. La economía ecológica (EE) se estableció formalmente en 1989 con el ambicioso plan de transformar las relaciones sociedad-naturaleza orientándolas hacia la sostenibilidad, entendida ésta como el respeto por los procesos ecológicos. Coincidiendo recientemente con los 30 años del establecimiento de la disciplina, y en vista de la actual coyuntura, diversos autores han reflexionado sobre la necesidad de una vuelta a sus orígenes, emplazando la comprensión biofísica del proceso económico en el centro de la agenda deinvestigación. En la presente comunicación se argumenta que la metodología Multi-

ScaleIntegrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) es una excelente candidata para dar operatividad a este ambicioso plan. Para ello se expone de una manera clara y accesible las principales características del enfoque. Además, diversos conceptos teóricos que fundamentan la metodología son revisados y relacionados con pilares conceptuales de la EE como la inconmensurabilidad de valores o la sostenibilidad fuerte. Finalmente se reflexiona sobre el potencial de MuSIASEM para vislumbrar espacios de cambio que promuevan unas prácticas sociales más sostenibles.

Palabras clave: MuSIASEM, metabolismo social, análisis biofísico, complejidad.
Clasificación JEL: Q57.

1. Introducción.

La actual crisis sociosanitaria de la COVID-19 pone de relieve las profundas interdependencias entre sistemas humanos y naturales. La presión ejercida por las sociedades humanas, materializada en términos de destrucción de la complejidad de los ecosistemas regionales, de desforestación y de producción de espacios urbanos, junto con un sistema económico global hiperconectado, han sido factores claves para la emergencia de la pandemia (Wallace et al., 2020). En un sentido más amplio, conceptos como "Antropoceno", "Gran Aceleración", "Siglo de la Gran Prueba" o "Límites Planetarios" forman ya parte del imaginario colectivo e indican un deterioro ambiental incuestionable producido por las presiones humanas sobre el mundo natural (UN Environment 2019) que pone en peligro la continuidad del equilibrio planetario y la sostenibilidad de las sociedades humanas (Steffen et al., 2018).

Lejos de aceptar esta realidad, la economía ortodoxa (EO) mantiene una visión que ignora la dependencia de los sistemas socioeconómicos del macrosistema natural y la consiguiente existencia de procesos fuera de control humano que imponen límites. El objeto de la ciencia económica y la definición de riqueza social, se reduce al estudio de los bienes y servicios apropiables, valorables (en dinero), intercambiables y producibles. A su vez, la representación del proceso económico se encuentra enclaustrada en el universo autosuficiente de los valores de cambio, con la consiguiente separación entre escasez subjetiva y objetiva y entre lo económico y lo físico (Naredo 1987). En consecuencia, la perspectiva reduccionista de la EO respalda políticas que destruyen los ecosistemas y los fundamentos sobre los que se sustenta la vida (Røpke 2005).

Con el convencimiento que las herramientas propuestas por la EO son insuficientes para representar las complejas relaciones sociedad-naturaleza y tratar la crisis ambiental, la economía ecológica (EE) se estableció formalmente en 1989 con el ambicioso plan de desarrollar un nuevo paradigma económico basado en la dependenciade los sistemas sociales y económicos de una realidad biofísica que los sustenta y los limita (Daly 1977; Georgescu-Roegen 1971). Bajo un marco ontológico radicalmente diferente al de la EO, la EE propone una narrativa termodinámica del proceso económico.La perspectiva de la EE, sin caer en el reduccionismo, considera a las sociedades humanas como sistemas naturales y a los procesos económicos como procesos metabólicos que deben ser caracterizados en términos de flujos de energía y materiales. El objetivo final de la disciplina era proveer con nuevas herramientas epistemológicas para la comprensiónde la escala, el uso de recursos e impactos generados por las sociedades humanas a la vez que ofrecer políticas alternativas para transformar las sociedades hacia la sostenibilidad (Røpke 2004; Spash 2015). Posteriormente la EE se ha embarcado en una fase de pluralismo metodológico y transdisciplinariedad, que le han hecho perder sus raíces heterodoxas para hacerla más compatible con la EO (Melgar-Melgar y Hall 2020; Spash 2020). Así, las aproximaciones monetarias y basadas en mecanismos de mercado han ido ganando peso con respecto a enfoques biofísicos (Plumecocq 2014).

Tras más de treinta años desde el establecimiento formal de la EE se hace cada vez más patente el carácter interrelacionado y sistémico de la crisis ambiental, que también es económica y social. Asímismo, la incapacidad de la EO, convertida en instrumento de estabilización de la actual estructura de poder, para hacerla frente apoyadaen sus dos principales paradigmas: el crecimiento económico ilimitado y las valoraciones monetarias y el uso de mecanismos de mercado (Giampietro y Funtowicz 2020). En este sentido, diversos autores abogan por una vuelta de la EE a sus orígenes más heterodoxos y contestatarios, emplazando la comprensión de los sistemas socioeconómicos en términos biofísicos y el rechazo a los presupuestos de la EO, en el centro de la agenda deinvestigación (Daly 2019; Melgar-Melgar y Hall 2020; Pirgmaier y Steinberger 2019; Spash 2020).

En la presente comunicación se presenta a la metodología *Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism* (MuSIASEM) como una excelente candidata para dar operatividad al ambicioso plan fundacional de la EE ahora de nuevo reivindicado. En una aproximación biofísica o ecointegradora (Naredo 1987) el proceso de reproducción social debe contextualizarse siempre bajo una permanente y cambiante relación metabólica con la naturaleza (Harvey 2010). Esto se traduce en la necesidad de herramientas que aporten información relativa a la disponibilidad de recursos, generación de residuos, uso de los distintos flujos metabolizados en el interior del sistema socioeconómico, producción de presiones e impactos ambientales y el reconocimiento de incertidumbres fuertes (efecto rebote, paradoja de Jevons, dificultades epistemológicas, etc.). MuSIASEM es un enfoque innovador para el estudio de la sostenibilidad de las sociedades humanas que da respuesta a estas necesidades. Es una de las principales metodologías en el campo de la investigación sociometabólica (Haberl et al., 2019) que asu vez está relacionada con una vieja tradición en el campo de la teoría económica: el estudio substantivo (en especie, "in natura") de la economía. De acuerdo con Gerber y Scheidel (2018) MuSIASEM es una de las principales metodologías para el estudio substantivo del proceso económico de una manera sistémica.

La originalidad de MuSIASEM radica en poseer unas robustas bases teóricas basadas en la integración de diferentes ideas y conceptos de la ciencia de la complejidad (Giampietro et al., 2012, 2013; Giampietro y Renner 2020; Renner et al., 2020). Debido a su especificidad, el principal objetivo de la comunicación es presentar la metodología de manera accesible en lengua castellana a la vez que clarificar y discutir algunos de sus conceptos teóricos para facilitar su comprensión e incentivar su aplicabilidad. En este sentido la presentación se organiza como sigue: en la siguiente sección se presentan ideas básicas de la metodología en relación a su aproximación al sistema económico, al proceso económico y a la sostenibilidad. El apartado tercero revisa y discute varios conceptos teóricos habituales en la literatura sobre la metodología. Finalmente, la comunicación se cierra con algunas consideraciones finales.

2. MuSIASEM: nuevas perspectivas para los retos actuales.

Desde la perspectiva de MuSIASEM los sistemas sociales y los sistemas naturales son sistemas complejos autoorganizados y deberían ser estudiados conjuntamente como un sistema interdependiente (Giampietro 2019a). Este punto de vista reconoce que el funcionamiento de los ecosistemas es decisivo, no sólo por la provisión de recursos naturales y como sumidero de desechos, sino porque provee con una gran variedad de servicios ecológicos sin los cuales las sociedades humanas no podrían florecer (ciclo hidrológico, regulación del clima, mantenimiento de la composición atmosférica, renovación de fertilidad suelos, etc.). Además, el estado de un sistema de estas características no es observable ni controlable a través de precios y valoraciones monetarias.

El hecho de considerar a un sistema como complejo presenta indudables retos epistemológicos. Por un lado, el comportamiento del todo no es evidente del estudio de sus partes. Hay que tener en cuenta el patrón, entendido como una configuración de relaciones determinada (Capra 1996). Así, desde la perspectiva de MuSIASEM el sistema socioeconómico se entiende como una totalidad integrada que emerge de las relaciones organizadas entre sus partes. Por otro lado, la complejidad implica tener en cuenta el punto de vista del observador y la existencia de percepciones no equivalentes de lo que es relevante a la hora de representar un fenómeno (Ahl y Allen 1996). Un enfoque desdela complejidad reconoce la existencia de inconmensurabilidad social y técnica. La primerahace referencia a la existencia de diferentes actores con valores opuestos y diferentes percepciones e intereses. La segunda a la imposibilidad de resumir todas las posibles representaciones a una única dimensión o escala (Giampietro et al., 2012). Con el objetivode obtener una caracterización lo más completa posible del sistema económico, MuSIASEM integra diferentes dimensiones (económica, biofísica, demográfica y ecológica), considera diferentes niveles de análisis (la totalidad del sistema, compartimentos y subcompartimentos) y aplica diferentes escalas temporales y espaciales(Giampietro y Mayumi 2010). Todo ello representa un punto de partida radical para el estudio del metabolismo social que contrasta con visiones reduccionistas basadas en la adopción de una única escala y una única dimensión.

Diversas ramas de la teoría de la complejidad sugieren una fuerte analogía entre los procesos autoorganizados de los sistemas ecológicos y de los sociales (Giampietro y Renner 2020; Renner et al., 2020). Ambos requieren la existencia de favorables condiciones ambientales para su desarrollo y la habilidad de poder usar los recursos disponibles (Giampietro 2019b). Así, desde la narrativa metabólica que utiliza la metodología, se concibe al sistema económico como un sistema disipativo. Este tipo de sistemas necesitan constantemente obtener inputs de su medio ambiente (energía ymateriales) y poder depositar en él desechos para mantener su identidad y estructura interna (Prigogine y Nicolis 1977). Son disipativos en el sentido de que tienen estructura pero no la estabilidad de los sólidos: se disipan cuando el suministro de energía se acaba. Por consiguiente son sistemas en reacción continua capaces de compensar su ritmo de generación de entropía interna a expensas de la energía libre tomada del medio ambiente y devuelta al mismo en forma degradada.

El uso de la metodología MuSIASEM implica modificar nuestro nivel de observación en el análisis de un sistema socioeconómico. La unidad de estudio no es un sistema económico aislado y autosuficiente (o con intercambios con el exterior meramente en términos de comercio exterior) sino un sistema socio-ecológico, formado por dos elementos básicos: la tecnosfera y la biosfera. El primero incluiría un conjunto de agentes sociales, instituciones y artefactos bajo control humano (lo que vendría a ser un sistema socioeconómico desde la visión convencional) que genera la cantidad de entropía positiva necesaria para el mantenimiento de sus estructuras internas y la expresión de lasfunciones asociadas a la identidad del sistema. El segundo, por su parte, englobaría a un conjunto de ecosistemas que compensaría la destrucción de gradientes favorables por la estructura disipativa (Giampietro 2019a).

Partiendo del trabajo de Georgescu-Roegen (1971), MuSIASEM también nos incita a repensar el proceso económico. El economista rumano consideraba que lafinalidad última del proceso económico es el disfrute de la vida y que el valor se deriva del flujo inmaterial generado por la producción (si bien materia y energía de baja entropíay trabajo humano son elementos indispensables del proceso de producción). Siguiendo esta línea de razonamiento, en MuSIASEM el sentido último del proceso económico no es la producción aumentada de bienes y servicios sino asegurar el mantenimiento y la reproducción de los componentes constituyentes (o elementos estructurales) de la sociedad, básicamente personas y unos usos del suelo determinados. Para ello se hace necesaria la existencia de un conjunto de elementos funcionales que garanticen una serie de usos finales o prácticas sociales imprescindibles para la reproducción social (por ejemplo, un sector agrícola que produzca alimentos, un sistema de transporte que nos permita la movilidad, un sector doméstico que asuma la crianza y cuidado de las personas, etc.). Por su parte, el concepto de patrón metabólico, una de las ideas clave de la metodología, haría referencia a los requerimientos de energía y materiales del conjunto de componentes funcionales. Este puede ser expresado como ratios metabólicos en términos de uso de recursos por hora de actividad humana o densidades metabólicas en términos de requerimientos de recursos para los diferentes usos del suelo (agrícola, industrial, residencial, etc.). Evidentemente, economías con diferentes configuraciones deelementos estructurales y funcionales generarán patrones metabólicos distintos.

MuSIASEM habilita un análisis de la sostenibilidad basado en una caracterización cuantitativa del patrón metabólico del sistema bajo estudio. Para ello la metodología utiliza diferentes niveles de observación: (i) una visión interna, relacionada con el concepto de "viabilidad" y asociada a procesos bajo control humano sujetos a limitaciones internas (relacionadas con la tecnología disponible y las instituciones y capacidades humanas); (ii) una visión externa relacionada con el concepto "factibilidad" y asociada a procesos fuera de control humano sujetos a limitaciones externas (por ejemplo, disponibilidad de fuentes de energía primaria o la capacidad de absorción de desechos de los ecosistemas); y (iii) una visión normativa relacionada con el concepto de "deseabilidad" asociada a la compatibilidad con valores sociales (Giampietro et al., 2014).

La visión interna estudia el modo en que los diferentes elementos funcionales de la tecnosfera metabolizan diferentes inputs (por ejemplo vectores energéticos como la electricidad o el gasoil) para realizar su cometido. Este análisis se realiza con la matriz deusos finales (Velasco-Fernández et al., 2018; Velasco-Fernández et al., 2020). La visión externa, por su parte requiere, contemplar la existencia de un adecuado aporte de inputs desde la biosfera a la tecnosfera (en términos por ejemplo de fuentes primarias de energíacomo el petróleo o el carbón) y la generación de desechos y emisiones desde la tecnosferaa la biosfera. La metodología dispone de la matriz de presiones ambientales y la matriz de impactos ambientales para realizar este análisis (Ripa y Giampietro 2017). Finalmente, la deseabilidad del patrón metabólico requiere una reflexión sobre la identidad de la sociedad, sus valores y creencias, que va más allá de consideraciones cuantitativas y debeser realizado en un marco de ciencia posnormal (Funtowicz y Ravetz 1993).

En conclusión, en un mundo donde todas las partes están conectadas, reducir la presión sobre uno de los varios límites ecológicos generará nuevas presiones en otros límites. En este sentido, el estudio de la sostenibilidad presenta indudables retos. MuSIASEM permite analizar la sostenibilidad de un sistema socioeconómico integrandodiferentes niveles de observación: la relación de las partes con el todo (visión interna), larelación del todo con el contexto (visión externa), expresada en términos de generación de presiones ambientales, y la relación entre identidad y contexto a medida que se interactúa y se modifica constantemente el entorno (visión normativa).

Una vez planteadas las ideas generales de la metodología, el siguiente apartado presenta y discute diferentes conceptos teóricos relevantes en la literatura sobre MuSIASEM con el objetivo final de incentivar su aplicabilidad desde la riqueza de sus fundamentos teóricos.

3. Conceptos teóricos.

3.1. Proceso semiótico

Las sociedades humanas mantienen una relación dialéctica con su medio ambiente y por eso deben estar permanentemente adaptándose a las nuevas condiciones que, en parte,han creado. En este sentido son sistemas anticipativos (Rosen 1985) que necesitan del usode modelos, sobre su interacción con el medio ambiente y con otras sociedades, para aprender y adaptarse. A su vez, la producción de conocimiento científico es clave a la hora de generar modelos anticipativos que posibiliten la sostenibilidad. Sin embargo, las afirmaciones científicas han de ser validadas y el proceso de generación de conocimiento científico se encuentra insertado en un proceso más amplio de producción de sentido y construcción de realidad que define las prioridades de la sociedad en su conjunto: el proceso semiótico (Giampietro 2019b).

Desde un punto estrictamente conductivista, el comportamiento de todo organismo puede denominarse "intencionado" al tratarse de un comportamiento dirigido a un objetivo. Los sistemas vivos validan la utilidad de sus modelos a través de un procesode interacción con el mundo exterior basado en la autoregulación desde la retroalimentación (Capra 1996). Percepciones relevantes del mundo exterior (semántica) son trasladadas a representaciones útiles (sintaxis) con las que guiar la acción (pragmática). El resultado del proceso es evaluado en referencia a los resultados previstos por el modelo. Si lo ocurrido difiere de lo esperado nuevos modelos explicativos deben ser generados hasta llegar a lo que Pattee (1995) denomina "cierre semántico" en donde todos los pasos entre semántica, sintaxis y pragmática son coherentes.

En el caso particular de las sociedades humanas obtener un "cierre semántico" es especialmente complicado, en particular en temas relacionados con la sostenibilidad en donde diferentes agentes tienen diferentes percepciones y representaciones relevantes sobre lo que es pertinente. En este sentido cuatro componentes pueden ser identificados en el proceso semiótico de las sociedades humanas: (i) el conocimiento científico aportando las representaciones; (ii) la gobernanza generando las interpretaciones; (iii) unconjunto de prácticas sociales; y (iv) un proceso político que define la identidad social yque determina las alternativas a considerar y la jerarquía de prioridades a resolver por la sociedad en su conjunto. El proceso semiótico revela el hecho de que los mecanismos deconstrucción de valor y significado tienen lugar a una escala que no puede atribuirse a organismos aislados. Sin embargo, debido a la existencia de asimetrías de poder en el ámbito político es importante evitar la hegemonización de perspectivas y agendas acerca de los problemas que deben ser resueltos. Además el proceso de filtraje y compresión de visiones consideradas relevantes debería ser permanentemente actualizado (Giampietro 2019b). La preocupación con respecto al cambio climático, que ha pasado de un asunto limitado a la percepción de unos pocos ecologistas hasta la consideración de un problema institucional, parece un buen ejemplo de identificación de nuevos problemas en el senode la sociedad.

Las implicaciones del concepto de proceso semiótico son importantes de cara a la aplicación de MuSIASEM como herramienta cuantitativa de análisis de la sostenibilidad. Los modelos científicos son una representación simplificada de una percepción compartida de la realidad, no la realidad misma (Giampietro 2003). Hay un punto de vista del observador que debe ser integrado en el propio proceso de conocimiento. Este punto de vista se materializa en la decisión preanalítica sobre cómo observar. La selección de modelos, datos y la monitorización de resultados que resulta en hechos científicos es el resultado de la elección original acerca de qué narrativa utilizar y de qué preocupación relevante tratar. Sin embargo, la elección sobre el determinado problema que debe ser tratado no se puede justificar científicamente, más bien refleja una decisión normativa producto de un particular proceso político. Así, una definición estrecha de los problemas relevantes que deben ser tratados, que refleje sólo el interés de un grupo limitado de actores sociales, genera "hipocognición" (Lakoff 2010), esto es, un marco de análisis simplista que silencia aspectos importantes a considerar.

Finalmente, la idea de proceso semiótico nos remite a las causas sociales profundas de, entre otras cosas, el deterioro ambiental. Las prácticas sociales son el resultado del proceso de definición de identidad y de los problemas relevantes que deben ser solucionados. En la mayoría de sociedades actuales el proceso semiótico esta hegemonizado por un conjunto de narrativas económicas producto del sistema capitalista dominante. El marco de producción y reproducción capitalista se centra en el valor de cambio y la reproducción ampliada del capital obviando cualquier tipo de realidad biofísica (Harvey 2018; Pirgmaier y Steinberger 2019). Si bien este modelo pudo ser instrumentalmente útil en un contexto de "mundo vacío" para expandir la capacidad de captar y transformar bienes naturales en bienes y servicios útiles para las sociedades, seguir manteniendo tal marco aspiracional deja de tener sentido en un "mundo lleno" donde la destrucción creativa está disparando los riesgos de colapso de las sociedades (Daly 2005). Así, el problema no es sobre una entidad ontológica a la que hay que combatir (por ejemplo el cambio climático) sino sobre un sistema que promueve prácticas insostenibles como resultado de un proceso semiótico concreto y que responde a preguntas del tipo: "¿quiénes somos como sociedad?", "¿cuáles son nuestras metas?", "¿somos consumidores soberanos o seres ecodependientes e interdependientes?".

Si como sugiere Harvey en relación a su utopismo dialéctico, toda naturaleza, incluida la humana, trata de la exploración de lo novedoso (Harvey 2019), MuSIASEM debería ser usado como una herramienta para estudiar cómo la sociedad debería cambiarsu identidad para hacerla compatible con su entorno, ayudando a definir un espacio para unas prácticas sociales realmente sostenibles.

3.2. Gramáticas

La sostenibilidad implica cambio: una variedad de sistemas humanos se adaptan e influyen sobre el medio ambiente y, en cierto punto, hacer más de lo mismo pone en riesgo su mantenimiento y reproducción (Giampietro 2003). Con la finalidad de caracterizar diferentes sistemas socioeconómicos, y poder representar su cambio, son necesarias herramientas epistemológicas flexibles que nos permitan introducir nuevas funciones y elementos estructurales. En este sentido la metodología cuenta con gramáticas las cuales facilitan una representación pertinente de las actividades metabólicas del sistema bajo estudio (Giampietro et al., 2012).

La noción más familiar del concepto de gramática está asociada con la organización estructural del lenguaje (Chomsky 1998). En el caso particular de laconfección de modelos cuantitativos, el uso de gramáticas es útil para dotar de estructuraoperacional a la fase preanalítica. Esto implica la selección tanto de las categorías semánticas (usadas para que el análisis tenga sentido) como de las categorías formales (usadas para la cuantificación). En otras palabras, con las gramáticas podemos respondera las preguntas "¿qué es el sistema?" y "¿qué hace el sistema?" (Giampietro et al., 2012; Giampietro et al., 2014).

MuSIASEM ha desarrollado gramáticas específicas para la cuantificación de los requerimientos de energía, agua y alimentación así como para la cuantificación de la actividad humana y los usos del suelo. Estas gramáticas pueden ser consideradas como mapas relacionales que permiten describir en términos cuantitativos la red de conversiones de los flujos de energía, agua y alimentación que se producen en el seno del sistema socioeconómico una vez definida su taxonomía, es decir, los elementos funcionales y estructurales que lo componen (Giampietro et al., 2014).

Las gramáticas abordan el problema de la escala mediante una bifurcación de las categorías semánticas en relación a la visión interna y la externa. Así en la visión externa las categorías usadas son fuentes primarias (por ejemplo, carbón y petróleo para la energía, suelo fértil para la alimentación o acuíferos para la cuantificación de los requerimientos de agua). La visión interna, por su parte, es caracterizada en términos de vectores energéticos y usos finales (por ejemplo electricidad y combustibles para la energía, consumo de carne para la alimentación o agua potable para los requerimientos de agua). Con ello obtenemos una caracterización que integra tres niveles: (i) la escala local, que nos informa de cómo diferentes elementos estructurales usan los flujos biofísicos para la generación del output deseado junto con la inevitable producción de residuos; (ii) la mesoescala, que identifica el conjunto de elementos funcionales capaces de expresar un conjunto de usos finales que garantizan la reproducción del sistema; y (iii) la gran escala que analiza procesos fuera de control humano en relación a la disponibilidad de recursos y asimilación de desechos (Giampietro et al., 2014).

Si bien el proceso de aplicación de las gramáticas está estandarizado en MuSIASEM, estas pueden ser utilizadas "a la carta" por los agentes sociales. Así, dependiendo de la definición del problema, es posible desarrollar representaciones basadas en diferentes combinaciones de categorías semánticas y formales que permitan discutir la relevancia del punto de vista de un observador determinado. En este sentido, MuSIASEM ha sido utilizado para una gran variedad de análisis de sostenibilidad más allá de la caracterización del metabolismo de energía, agua y alimentación como es el estudio de la gestión de los residuos urbanos (D'Alisa et al., 2012) o el análisis integradode los sistemas agrarios (Scheidel y Farrel 2015).

En definitiva, el uso de las gramáticas en MuSIASEM garantiza la transparencia de las decisiones tomadas tanto en la fase preanalítica como en la fase descriptiva. Las gramáticas son una herramienta flexible que facilita la definición del sistema complejo bajo estudio y la elección de los atributos relevantes a cuantificar. Además, permiten una discusión informada de la sostenibilidad gracias a que son transparentes respecto a la manera en que han sido producidos los números.

3.3. Holon

El término de "holon" fue propuesto por Arthur Koestler (1967) para conceptualizar el problema epistemológico consistente en el hecho de que algunas entidades consideradas como totalidades no pueden ser comprendidas sin hacer referencia al contexto con el que interactúan. Candidatos para ser etiquetados como holones incluye acélulas, órganos, individuos humanos y sistemas socioeconómicos. Todos ellos realizan funciones como una totalidad a la vez que intercambian energía, materiales e informacióncon su medio ambiente. A su vez, el concepto de holon enfatiza la organización jerárquicade los sistemas vivos (Ahl y Allen 1996; Allen y Starr 1982; Giampietro 1994). Así, dependiendo de la escala adoptada para representar un sistema complejo, un elemento puede ser considerado como un todo estructural o una parte funcional de un nivel jerárquico superior. Esta doble naturaleza de los holones, explica la ambivalencia sistémica a la que un observador se enfrenta a la hora de representar elementos de sistemas complejos (Giampietro y Mayumi 2018).

El análisis relacional de Robert Rosen utiliza las cuatro causas aristotélicas para analizar un holon y determinar los elementos a observar y estudiar (Renner et al., 2020):
(i) un holon debe tener una función relevante, es decir, evidenciar una causa final; (ii) suproducto útil, que puede ser material o inmaterial, sólo puede ser expresado por el adecuado tipo funcional, es decir, garantizar una causa eficiente; (iii) el tipo funcional debe estar compuesto de la combinación adecuada de tipos estructurales con lo que se hace necesaria la existencia de una causa formal; y (iv) una causa material, es decir diferentes configuraciones de energía, materiales y trabajo humano, son requeridos para su existencia. El uso de esta terminología aristotélica revela el carácter complementario yno substitutivo entre recursos naturales, capital y trabajo, alineándose con la visión de laEE, e invalidando el principio de sostenibilidad débil.

Una segunda complicación epistemológica relacionada con el concepto de holon proviene de la degeneración sistémica en el mapeo de sus componentes (Giampietro y Mayumi 2018). Un tipo funcional (por ejemplo, un profesor) puede relacionarse con diferentes tipos estructurales (hombre y mujer de diferentes edades) y un mismo tipo estructural (por ejemplo, una persona) puede realizar diferentes funciones (profesora, madre y cantante de coro). Además, la identidad de un tipo (su descripción ideal) nunca coincide exactamente con su realización específica, es decir, un caso concreto de combinación de un tipo funcional con un tipo estructural (las profesoras, madres y cantantes de coro son todas especiales). Así, al representar los elementos de un sistema complejo pensamos en tipos ideales (por ejemplo la granja, la fábrica, el coche, etc.) cuando en realidad sólo podemos observar casos concretos de esas tipologías conocidas (una granja, una fábrica, un coche, etc.). En la práctica esto implica reconocer un alto grado de contingencia entre las posibles combinaciones de tipos funcionales, tipos estructurales y realizaciones concretas (Giampietro 2019b).

El concepto de holoarquía, jerarquía de holones, es útil a la hora de emplear diferentes narrativas al tratar con sistemas complejos. Dentro de una holoarquía existe una tensión entre la causalidad descendente (definición de limitaciones determinadas porla actividad de los holones de nivel superior) y la causalidad ascendente (tendencias generadas por la actividad de holones de niveles inferiores). En una holoarquía saludableesta tensión es conservada, característica conocida con el nombre de equipolencia (Iberallet al., 1980). La pérdida de equipolencia se manifiesta en el dominio de determinadas perspectivas y narrativas sobre otras perspectivas legítimas y opuestas. La sostenibilidad de los sistemas humanos nos permite pensar en estos términos. Las economías humanas se han expandido tanto como holones que están poniendo en peligro la estabilidad de los niveles superiores (sistema ecológico) de la holoarquía a la cual pertenecen. Además, el uso de narrativas económicas no es suficiente para explicar el cambio sistémico (Giampietro 1994).

Por último, el concepto de holon está relacionado con la existencia de una pluralidad de visiones y observadores. Los agentes humanos son holones y expresan simultáneamente diferentes identidades en una ecología de contextos. Los diferentes contextos son inconmensurables y no pueden compararse entre ellos o convertirse a una unidad común de medida (Bland y Bell 2007). Así, la capacidad de expresar la función prevista de una persona como padre, profesor o vegano refuerza o debilita la definición específica de sus contextos. También, las sociedades humanas son holoarquías en las que coexisten diferentes definiciones de identidad y propósito con respecto a diferentes holones de la jerarquía. Individuos, hogares, comunidades locales, gobiernos nacionales, etc., cada uno se encuentra en búsqueda de su propio "cierre semántico" dentro de su propio proceso semiótico (Giampietro 2019b).

Las ideas expuestas reverberan con fuerza en MuSIASEM. La existencia de diferentes observadores, el uso de distintas narrativas y el acoplamiento forzoso entre función y estructura son líneas de pensamiento constantes de la metodología. En términosprácticos esto se traduce en la adopción de dos visiones complementarias de análisis. Unenfoque de arriba hacia abajo que considera las relaciones funcionales entre los elementosdel sistema y un enfoque de abajo hacia arriba para el estudio de los elementos estructurales que componen los diferentes compartimientos funcionales. Esta doblecaracterización permite combinar evaluaciones multidimensionales procedentes de datosestadísticos con evaluaciones basadas en coeficientes técnicos observados al nivel local, garantizando la robustez del análisis.

3.4. Autopoiesis

Autopoiesis, del griego, significa "creación de sí mismo". De acuerdo con Luisi (2003) el estudio de la organización autopoiética de los sistemas vivos, en su forma original, se limitó a la vida celular. Una célula es un sistema disipativo que mantiene su estructura interna gracias a una membrana esférica semipermeable que separa a la célulade su contexto. A partir de esta observación, Maturana y Valera (1980) identificaron la organización circular como la organización básica de todos los organismos vivos. Así, unsistema vivo es un sistema autopoiético en donde la función de cada componente es ayudar a producir y transformar a otros componentes manteniendo al mismo tiempo la circularidad global de la red (Capra 1996).

Junto con la expresión del patrón básico de organización de lo vivo, el concepto de autopoiesis está también relacionado con el fenómeno de la percepción. Un organismo vivo reconoce y utiliza el medio ambiente en un proceso en el que no hay separación entre el acto cognitivo y la estructura interna del mismo (Luisi 2003). En otras palabras, la percepción no puede ser considerada como una representación de una realidad externa sino que se especifica a través del proceso de cognición (Capra 1996). Los sistemas vivos poseen mecanismos que les posibilitan la obtención de información del exterior y la generación de significado válido para guiar su acción. Obtienen del mundo exterior los elementos que les permiten construir su identidad lo que les permite aprender, desarrollarse y adaptarse. En este sentido, la evolución es vista como el resultado del mantenimiento y adaptación de la estructura interna del organismo autopoiético en respuesta a cambios en las condiciones de su entorno (Giampietro 2019b).

Finalmente, autopoiesis también se vincula a la aparición de nuevos significados asociados a la aparición de nuevas funciones observables en un nivel diferente de análisis. Propiedades emergentes son aquellas nuevas propiedades que surgen cuando un conjunto de componentes se ensamblan generando una estructura de mayor complejidad. Así, por ejemplo, la vida de una célula es una propiedad global que no puede ser atribuida a un solo componente. Lo local y lo global se correlacionan de un modo dialéctico que enfatizala múltiple causalidad y contrasta con una visión mecanicista de la vida (Luisi 2003).

El concepto de autopoiesis es relevante en MuSIASEM. Desde la metodología las sociedades humanas son consideradas un caso especial de sistemas autopoiéticos en los cuales la definición de identidad se produce mediante un proceso semiótico que garantiza su mantenimiento, reproducción y adaptación. También, al igual que otros sistemas vivos, son sistemas disipativos alejados del equilibrio térmico con lo que necesitan un constante aporte de energía y materiales para el mantenimiento de su organización interna. Así, dependiendo del nivel de observación considerado podemos hacer una distinción entre: (i) el sistema autopoiético en su totalidad formado por el conjunto de elementos constituyentes que deben ser mantenidos (los elementos fondo del sistema); (ii) holones funcionales del nivel jerárquico inmediatamente inferior, cuya ensamblaje determina la propiedad emergente global, es decir, la existencia de la sociedad como un todo; y (iii) holones de niveles jerárquicos inferiores necesarios para el correcto desempeño de las diferentes funciones.

La actualización del proceso autopoiético, es decir, la constante reconfiguración y evolución de la identidad del sistema, es analizada bajo la emergencia de nuevos holones. El hecho de que la misma función pueda ser realizada por diferentes tipos estructurales, de que un tipo estructural pueda realizar diferentes funciones y de que la realización específica de un holon no sea exactamente predecible a partir de sus tipos ideales, permite a un sistema complejo un cambio no determinista en respuesta a requisitos internos o externos. Cuando un holon es introducido para cumplir una nueva función hablamos de innovación por emergencia. Por contra, cuando nuevos tipos estructurales son desarrollados para expresar mejor una función establecida nos referimos a innovación por diseño (Giampietro y Mayumi 2018). Un ejemplo de innovación por emergencia sería lanueva función de movilidad asociada a la electricidad con la implantación del vehículo eléctrico. Este tipo de innovaciones están asociadas a cambios en las condiciones marco (por ejemplo el cambio climático) o cambios en las expectativas del sistema (por ejemplo la necesidad de reducir las emisiones de la economía). La innovación por diseño se relaciona con situaciones de estabilidad. Un nuevo modelo de vehículo que nos permita conducir más kilómetros y de una manera más confortable sería un ejemplo de este tipo de innovaciones basadas en "hacer mejor lo mismo".

En definitiva, el concepto de autopoiesis dirige nuestra atención a los requerimientos para el mantenimiento de las sociedades humanas pero también a su carácter cambiante y adaptativo. En lo que respecta a una caracterización cuantitativa desistemas complejos esto es especialmente relevante. La validez del análisis se limita al mantenimiento de la identidad del sistema. Sin embargo, la constante reconfiguración delos componentes de un sistema autopoiético hace explícita la limitada vigencia de una representación cuantitativa. Por esta razón el conjunto de relaciones numéricas generadas en MuSIASEM no se dirigen a la obtención de soluciones óptimas (como sucede con los modelos convencionales basados en premisas "*ceteris paribus*"), sino a la representación de un espacio de información para llevar a cabo evaluaciones contingentes (del tipo "y si...") que permiten evaluar las limitaciones o incongruencias de ciertas propuestas.

3.5. Modelo Fondo-Flujo

El modelo fondo-flujo es un pilar fundamental de la metodología. Desarrollado por Georgescu-Roegen (1971), cuyo trabajo fue seminal para el establecimiento de la EE como disciplina académica, el modelo fondo-flujo permite dotar de operatividad al análisis del metabolismo social desde MuSIASEM.

El término "fondo" hace referencia a los agentes que transforman flujos de entradaen un producto resultante mientras mantienen y preservan su identidad durante la duracióndel análisis. Los elementos fondo son los encargados de realizar las transformaciones metabólicas en los sistemas sociales. Ejemplos de elementos fondo son las personas, el capital fijo y la tierra. Por su parte los elementos flujo son aquellos utilizados por los elementos fondo para la realización de su función. Estos aparecen o desaparecen durante la duración de la representación. Ejemplos de elementos flujo son los combustibles fósiles, la comida o las emisiones generadas por procesos industriales. El estudio del metabolismo social utilizando un modelo fondo-flujo no se centra exclusivamente en la cuantificación de los flujos sino que conecta fondos (los agentes transformadores en diferentes procesos) con flujos (los elementos utilizados y disipados). Esto permite generar indicadores multinivel caracterizando rasgos específicos del sistema (Giampietroet al., 2012).

El uso de elementos fondo y flujo ayuda a la configuración de la definición preanalítica de la identidad del sistema a estudiar. Así, los diferentes elementos fondo distribuidos en diferentes compartimentos funcionales jerárquicamente organizados responden a la pregunta "¿qué es el sistema y qué debe ser mantenido?". Estos agentes son los elementos constituyentes del sistema y deben ser preservados y reproducidos para mantener la identidad del mismo. Además, estos elementos requieren de flujos para expresar el conjunto de funciones que permiten la reproducción social, respondiendo a lapregunta "¿qué hace el sistema?". A este respecto, las gramáticas establecidas por la metodología permiten la distribución y cuantificación de los diferentes elementos fondo y flujo.

La idea de que un nivel de organización jerárquico mayor que el individuo deberíaser considerado a la hora de describir los flujos de energía en las sociedades modernas, es algo que transmite la distinción entre fondos y flujos. En este sentido es útil distinguir entre energía endosomática y exosomática. La primera hace referencia a la energía contenida en los alimentos y que es necesaria para el mantenimiento de los procesos fisiológicos humanos. La segunda, en cambio, indica la energía que es utilizada fuera del cuerpo con el objetivo de amplificar el producto del trabajo humano y el control sobre suentorno. El uso generalizado de diferentes artefactos en la tecnosfera (tecnología e infraestructuras) tiene como efecto que una gran parte de conversiones de energía en el metabolismo de las sociedades corresponda a transformaciones exosomáticas, vinculadasa niveles jerárquicos de compartimentación social superiores al individual.

Finalmente es importante distinguir entre flujos cuyo origen es un stock de aquellos originados por un fondo. Esta distinción tiene importantes implicaciones para la sostenibilidad de los sistemas humanos. El uso de un fondo conlleva una limitación determinada por la estructura física del fondo. Así por ejemplo una vaca, un elemento fondo, requiere de un tiempo para producir un litro de leche y no es posible obtenerlo en menos tiempo. Esto implica la existencia de una relación entre el elemento fondo y el ritmo al que puede proveer el flujo correspondiente. Además, los elementos fondo deben ser periódicamente renovados lo que genera unos gastos adicionales para su mantenimiento. Sin embargo, en la medida en que el elemento fondo es reproducido en el tiempo, el flujo resultante de su utilización puede considerarse renovable. Por el contrario un stock, en principio, puede utilizarse a voluntad para la generación de un flujo pero el insumo que se deriva de ese stock no es renovable. Las economías modernas dependen, básicamente, de flujos originados por stocks (basados en la explotación de reservas de combustibles fósiles) para obtener los requerimientos de energía ensodomática y exosomática necesarios para la estabilidad del proceso de reproducción social. En consecuencia, una transición hacia un modelo más sostenible, como puede ser el uso de energías renovables bajo un marco fondo-flujo, implicará cambios radicales en el proceso de autopoiesis de los sistemas socioeconómicos.

3.6. Presupuesto Energético Dinámico

Herbert Spencer, uno de los padres fundadores de la sociología moderna, relacionabael progreso social con el excedente de energía (McKinnon 2010). Este último posibilitaba la diferenciación social y la viabilidad de actividades culturales más allá de las relacionadas con la satisfacción de las necesidades vitales básicas. Otros eminentes investigadores como Zipf (1941, 1949), Lotka (1922) y White (1943) han desarrollado esta idea desde diferentes disciplinas. El concepto de presupuesto energético dinámico enMuSIASEM reflexiona sobre el hecho de que un sistema socioeconómico debe simultáneamente invertir energía en generar energía a la vez que destinarla para la expresión de otras funciones como el mantenimiento y actualización de diversas instituciones sociales.

El concepto de presupuesto energético dinámico para el estudio de los sistemas socioeconómicos está basado en el trabajo previo realizado para la caracterización de los sistemas ecológicos. Así, en el análisis de las estructuras de los ecosistemas, Ulanowicz (1986) diferenció, dentro de la red de flujos de materia y energía que constituyen un ecosistema, dos estructuras funcionales básicas: el hiperciclo y la parte disipativa. La primera debe proveer con un necesario excedente de energía (después de descontar el consumo propio) al resto del sistema. La segunda expresa actividades esenciales pero quedegradan energía.

Siguiendo esta distinción conceptual, es posible asociar los diferentes compartimientos funcionales del sistema socioeconómico como pertenecientes al hiperciclo o a la parte disipativa. El hiperciclo (también denominado parte catabólica) comprende los procesos que tienen lugar en los sectores primarios, es decir, los sectores agrícola, pesquero, forestal, minero y energético. Estos sectores, aun consumiendo materiales y energía para estar operativos, garantizan el suministro para el consumo en otros compartimientos sociales. La parte catabólica utiliza fuentes primarias (petróleo, gas, tierra fértil, etc.) que son transformadas en inputs primarios (vectores energéticos, alimentos, etc.) para su uso por el resto de sectores económicos. Por el contrario, la partedisipativa (también denominada parte anabólica) corresponde a los procesos que tiene lugar en los restantes sectores de la economía en donde los inputs primarios son usados para generar flujos secundarios (sector industrial) o para actividades de transacción y gobierno (sector servicios y administraciones) y consumo final (sector doméstico) indispensables para garantizar la reproducción social. La fuerza del hiperciclo, definida como el nivel de excedente generado por unidad de trabajo humano, determina el tamañoy complejidad de las actividades que la sociedad puede mantener en la parte disipativa (Giampietro et al., 2012; Giampietro 2019a). En esencia esto supone que debe haber un equilibrio entre los requerimientos biofísicos necesario para expresar las diferentesfunciones sociales y el flujo que es generado por los compartimientos pertenecientes al hiperciclo. En caso contrario, como sucede por ejemplo en sociedades con un alto grado de especialización en el sector servicios, un excedente monetario debe ser generado paraimportar energía y materiales.

El balance interno entre el hiperciclo y la parte disipativa es útil para comprenderla complejidad de los sistemas sociales. La complejidad en las sociedades humanas puede ser definida como la habilidad de generar y mantener una diferenciación tanto en estructura como en comportamiento (Tainter 1988). Los componentes de la complejidad incluyen poblaciones crecientes, mayores habilidades técnicas, diferenciación y especialización social y la creciente producción de flujos de información. Así, la complejidad está asociada a un aumento de las funciones relacionadas con la parte disipativa. Como apunta Tainter (2006) la complejidad es clave para la sostenibilidad de las sociedades humanas actuando como un mecanismo para la resolución de problemas. Sin embargo el coste de la misma se materializa en la energía, trabajo, dinero y tiempo necesarios para mantener un sistema que crece para tener más partes, especialistas, regulación e información. En otras palabras, la complejidad requiere un mayor consumo de recursos y en paralelo una mayor fuerza del hiperciclo para procesarlos.

En las sociedades industriales la complejidad se mantiene gracias al uso mayoritario de energías fósiles. Esta estrategia externaliza los costes de la misma hacia el medio ambiente y las generaciones futuras. Por consiguiente, conectar los costes y beneficios de la complejidad es también considerar una visión del proceso económico desde una perspectiva biofísica.

3.7. Análisis Impredicativo

La impredicatividad está relacionada con el proceso de interacción y coevolución entre las partes y el todo. Una definición impredicativa es autorreferencial y dependientedel contexto. En las sociedades humanas la impredicatividad es fácil de entender: la reproducción de la sociedad depende de la producción de alimentos, que a su vez depende de competencias técnicas, que están relacionadas con un determinado nivel de educación que depende de otras funciones sociales y así sucesivamente. La impredicatividad entra en conflicto con las simplificaciones inherentes del reduccionismo y cuestiona las explicaciones unidireccionales de causalidad (Giampietro et al., 2012). Rosen (2000) considera la impredicatividad como una de los atributos de los sistemas autopoiéticos.

En MuSIASEM el análisis impredicativo (ILA), de *Impredicative Loop Analysis* en inglés, se utiliza para analizar las mutuas restricciones que se producen entre el todo y las partes de un sistema complejo. En este sentido, garantizar el equilibrio dinámico del metabolismo social de un sistema socioeconómico supone que diferentes parámetros, pertenecientes a diferentes niveles jerárquicos, deben ajustarse de un modo coordinado. El análisis impredicativo relaciona coeficientes técnicos o valores esperados definidos a un nivel jerárquico con el comportamiento de otros niveles diferentes. Así por ejemplo, podemos empezar con la definición de cuáles son las limitaciones externas a la que está sujeto el sistema (por ejemplo la tierra cultivable) y una determinación de los coeficientes técnicos (rendimientos por hora y hectárea) para calcular la cantidad de alimentos viables que pueden ser producidos o el nivel de suficiencia del sistema sin recurrir a externalizaciones (importar es una solución efectiva tanto para superar limitaciones externas como internas). O por el contrario, podemos empezar por fijar un determinado nivel material de vida para el conjunto de la sociedad y determinar los requerimientos técnicos y de actividad humana de un compartimiento determinado que serían necesarios para garantizar el cumplimiento de ese estándar.

Es importante destacar que el ILA no genera un resultado determinista. Cambios en las características de los niveles inferiores no necesariamente conducirán a cambios lineales en las características del conjunto del sistema. Cualquier combinación de cambios que se encuentre dentro del espacio de factibilidad, viabilidad y deseabilidad es admisible.La deseabilidad de una situación, esto es, una evaluación sujeta a preferencias humanas, es tan importante como la viabilidad técnica o la disponibilidad de recursos naturales para determinar la estabilidad de un determinado patrón metabólico. Sin embargo el ILA nos permite indagar en las respuestas a las preguntas sobre la sostenibilidad de un sistema humano del tipo: ¿cuánto cambiarán los requerimientos de energía y trabajo si aumenta la población o la calidad de la dieta? o ¿qué pasa en una sociedad en la que se incrementa la tasa de dependencia? Adoptar un enfoque multiescalar permite establecer vínculos entre limitaciones biofísicas (externas o internas) y su relación con diferentes niveles de observación (el todo y las partes).

El análisis impredicativo implica relacionar parámetros de diferentes escalas temporales y espaciales. Hay parámetros, por ejemplo los coeficientes técnicos, que se refieren a escalas temporales y espaciales muy específicas, como puede ser el caso del rendimiento de una determinada explotación agrícola. Otros parámetros, como la tasa de dependencia, reflejan procesos demográficos de escalas temporales diferentes. Finalmente, hay otras variables, como lo que es considerado aceptable o ético, que reflejan procesos relacionados con la identidad cultural de la sociedad (Giampietro y Mayumi 2000).

En conclusión, el ILA nos permite analizar escenarios que no son factibles desdeun punto de vista biofísico, identificando factores críticos y conexiones entre valores numéricos pertenecientes a diferentes niveles jerárquicos que hacen posible el mantenimiento de un determinado patrón metabólico.

3.8. Efecto Mosaico

El efecto mosaico es un concepto que nos permite representar la distribución de los elementos fondo y flujo entre los diferentes compartimientos funcionales definidos a diferentes niveles jerárquicos. También nos muestra los resultantes ratios metabólicos que caracterizan los requerimientos de los diferentes flujos por unidad de fondo.

Gracias al efecto mosaico, y en la misma línea que el ILA, es posible establecer una relación entre diferentes niveles jerárquicos y mostrar la congruencia entre las características del conjunto del sistema, al nivel n, y las características de compartimentos situados en niveles inferiores (n-1, n-2, n-3, etc.). Así, se establece una relación donde el patrón metabólico resultante del sistema socioeconómico está constituido por la agregación de sus partes. Esto implica el cierre numérico del valor de las categorías formales usadas para la cuantificación de los elementos flujo y fondo. En este sentido, elvalor de la suma de los requerimientos biofísicos de los diferentes niveles jerárquicos considerados debe ser igual al valor del conjunto del sistema expresado en el nivel n. Así, el efecto mosaico es útil a la hora de mostrar requerimientos a diferentes niveles en una discusión informada.

El efecto mosaico en las sociedades modernas industriales presenta un claro desacoplamiento entre la distribución de las horas de actividad humana y los requerimientos de energía exosomática, es decir, la energía utilizada por el conjunto de artefactos de la tecnosfera. Los sectores primario y secundario usan una pequeña fracción del conjunto de las horas de actividad humana disponibles en la sociedad. Por ejemplo, de 8.760 horas per cápita anuales, el conjunto de los 28 países miembros de la UE destinaba de media en 2015 tan sólo 40 horas a agricultura y 160 horas a industria mientras se destinaban más de 520 horas a servicios (Velasco-Fernández et al., 2019). Sin embargo, necesitan grandes inversiones de energía exosomática, hecho que se constata en los altos ratios metabólicos (energía por hora de actividad humana) de estos sectores (en el caso de la UE-28 mencionado anteriormente el sector industrial llega a consumir más 400 MJ/h). En general, elevados ratios metabólicos están asociados a altos niveles materiales de vida y a la generación de presiones ambientales resultantes de los elevados requerimientos en materiales y energía del proceso económico (Velasco-Fernández et al., 2018).

3.9. Efecto Sudoku

MuSIASEM facilita una representación multidimensional, del patrón metabólico del sistema socioeconómico considerado, similar a la cuadrícula del popular juego matemático "sudoku". La información relacional de las gramáticas es condensada para obtener una cuantificación de las variables fondo (generalmente actividad humana y usos del suelo si bien la potencia instalada también puede ser considerada) y las variables flujo (básicamente energía, agua, alimentación, emisiones, residuos y flujos monetarios) asignadas a los diferentes compartimentos funcionales jerárquicamente ordenados. Con ello obtenemos un diagnóstico de los requerimientos biofísicos tanto al nivel del sistema como totalidad como de los diferentes sectores económicos (agricultura, energía y minería, manufactura y construcción, servicios y gobierno y sector doméstico). También, descendiendo en el nivel de observación, podemos obtener información biofísica acerca de procesos o tareas específicas dentro de los diferentes subcompartimentos económicos (por ejemplo el uso de energía y otros recursos en diferentes explotaciones agrícolas o enel sector turístico). En esencia, la caracterización facilitada por MuSIASEM permite obtener indicadores contextualizados que nos informan sobre qué tipos de energía y recursos son utilizados, por quién, cómo y para hacer qué.

MuSIASEM utiliza tanto variables intensivas como extensivas. Las primeras sonratios flujo-fondo que nos dan información sobre características metabólicas (tasas, por hora; densidades, por hectárea e intensidades, por kilovatio). Por su parte, las variables extensivas nos dan una idea del tamaño de los diferentes partes del sistema respecto a su totalidad y de sus respectivos requerimientos biofísicos. Un aspecto clave de MuSIASEMes el uso de indicadores "por hora de actividad humana" o "por hectárea de uso del suelo"aplicado a los diferentes compartimentos funcionales. La descomposición de la tradicional caracterización "per cápita" o "por hectárea" en subcategorias funcionales de usos del tiempo y del espacio permiten una mejor comprensión del metabolismo del sistema bajo estudio a la vez que facilita la simulación de escenarios. Además, es posibleutilizar valores de referencia, establecidos en la literatura sobre la metodología, bajo los cuales evaluar el desempeño económico o biofísico del sistema estudiado. Así, podemos comparar la dimensión económica de un determinado compartimento socioeconómico, por ejemplo energía consumida por hora en el sector servicios, o su dimensión ecológica,por ejemplo consumo de agua en el sector agrícola por hectárea, con valores promedio ocon otros territorios donde se están realizando estudios similares (Sorman 2015).

El modo en que los datos están representados, las filas muestran los sucesivos niveles jerárquicos y columnas las diferentes dimensiones de análisis, genera tres tipos de limitaciones o restricciones útiles a la hora de analizar el patrón metabólico o simular escenarios. En primer lugar aparece una restricción vertical que apunta a la competición por recursos. Los diferentes factores de producción (elementos fondo y flujo) en una sociedad son limitados de manera que si un compartimento funcional incrementa su utilización otros compartimentos deben reajustar su uso. En segundo lugar, la restricción horizontal hace referencia al límite en la posibilidad de sustituir factores de producción. Así, la combinación de factores debe ser tal que permita a cada fila, es decir, cada compartimento funcional, realizar su cometido. Finalmente, al igual que en el popular pasatiempo, existe una restricción de bloques. Los compartimentos que engloban el hiperciclo y aquellos que constituyen la parte disipativa deben mantener un equilibrio dinámico ya sea generado internamente o con la masiva importación de recursos (Giampietro y Bukkens 2015).

4. Consideraciones finales.

Los principales retos a los que se enfrenta la humanidad en el siglo XXI, entre los que se encuentran el cambio climático, la transición hacia un sistema energético basado en renovables o la pérdida de la biodiversidad, son biofísicos. Estos desafíos requerirán una redefinición del papel de las narrativas económicas en el seno de la sociedad así comoun cambio radical en las instituciones y un reajuste de las prácticas sociales. Asimismo, las iniciativas que se han articulado para dar respuesta a estas emergencias, recogidas enlos Objetivos del Desarrollo Sostenible (ODS), necesitan de la integración de información procedente de diferentes dimensiones (la biofísica, la económica, la social) y escalas de análisis. La situación actual precisa de respuestas desde la economía ecológica (EE). Para ello se hacen necesarios cambios en su aparato conceptual y metodológico que abandonen su adhesión a viejos paradigmas y se centren en una perspectiva basada en la complejidad que ponga los fundamentos biofísicos del proceso económico en el centro de la agenda de investigación.

En esta comunicación se ha presentado a la metodología MuSIASEM como una herramienta epistemológica que facilita una caracterización en esta dirección. Desde una ontología básica consistente en sistemas complejos adaptativos múltiplemente interdependientes, la metodología facilita un diagnóstico multinivel de los requerimientos de energía y materiales necesarios para el mantenimiento y la reproducción de los sistemas socio-ecológicos. En este sentido es posible obtener una serie de indicadores base, a partir de los cuales poder discutir posibles vías de transición hacia un desarrollo más sostenible. Además, la metodología se alinea bien con preceptos básicos de la EE como son el uso de indicadores provenientes de diferentes dimensiones y la inconmensurabilidad de valores.

Si bien MuSIASEM es una herramienta eminentemente cuantitativa, sus fundamentos teóricos nos invitan a reflexionar sobre que, en lo que se refiere a la sostenibilidad, hacer más y más números no tiene porqué ser la respuesta. La sostenibilidad de las sociedades humanas parece requerir un equilibrio sutil entre eficiencia, hacer más de lo mismo bajo una definición de identidad dada, y adaptabilidad,es decir, cambiar la identidad del sistema ante cambios en las condiciones ambientales. En otras palabras, no es el mundo exterior el que se tiene que adaptar a nuestros requisitosy deseos. Al contrario, es necesario adaptar nuestras expectativas a las limitaciones impuestas por el mundo exterior, lo que implica un proceso reflexivo y conflictivo sobre el modo en que realizamos nuestro particular proceso semiótico. A su vez, esta consideración nos invita a ser escépticos con posturas excesivamente optimistas con respecto al uso unilateral de innovaciones tecnológicas como medio para resolver los problemas de sostenibilidad. Estos últimos, también requerirán cambios sociales y culturales que se materializarán en nuevas reconfiguraciones de la sociedad y nuevas prácticas sociales. En este sentido, se hará necesario el saber aprender a balancear los intereses y convivir con los pros y los contras de las soluciones, sin dejar de reflexionar sobre los nuevos problemas que surgen de forma democrática y asumiendo que, si bien sólo podemos aspirar a cambiar los problemas, al menos esto se puede llevar a cabo de una forma reflexiva y bien informada.

En definitiva, el análisis del patrón metabólico nos permite una discusión informada sobre el proceso de cambio de las sociedades humanas. En este proceso, las restricciones biofísicas afectan el espacio de decisión. Si como afirma Tanuro (2020), nohay libertad sin que exista conciencia de los límites, MuSIASEM nos dirige hacia percepciones y representaciones en esa dirección.

Referencias bibliográficas

-Ahl, Valerie y Allen, T.F.H. (1996): *Hierarchy Theory*, New York: Columbia UniversityPress.

-Allen, T.F.H. y Starr, T. (1982): *Hierarchy: Perspectives for Ecological Complexity*,Chicago: University of Chicago Press.

-Bland, William L. y Bell, Michael M. (2007): “A Holon Approach to Agroecology”, *International Journal of Agricultural Sustainability* 5 (4), pp 280-94.

-Capra, Fritjof (1996): *La Trama de La Vida*, Barcelona: Anagrama, 2009.

-Chomsky, Noam (1998): *On Language*, New York: The New Press.

-D'Alisa, Giacomo; Di Nola, Maria Federica y Giampietro, Mario (2012):" A multi-scale analysis of urban waste metabolism: density of waste disposed in Campania", *Journal of Cleaner Production* 35, pp. 59-70.

-Daly, Herman E. (1977): *Steady State Economy*, San Francisco: Freeman.

-Dalyn Herman E. (2005): "Economics in a full world", *Scientific American* 293, pp. 78-85.

-Daly, Herman E. (2019): “Some Overlaps between the First and Second Thirty Years ofEcological Economics.”, *Ecological Economics* 164, pp.106-372.

-Funtowicz, Silvio O. y Ravetz, Jerome (1993): “Science for the Post-Normal Age.”, *Futures* 25 (7), pp. 735-55.

-Georgescu-Roegen, Nicholas (1971): *The Entropy Law and the Economic Process*, Cambridge: Harvard University Press.

-Gerber, Julien François y Scheidel, Arnim (2018): “In Search of Substantive Economics: Comparing Today’s Two Major Socio-Metabolic Approaches to the Economy – MEFA and MuSIASEM.”, *Ecological Economics* 144, pp. 186-94.

-Giampietro, Mario (1994): “Using Hierarchy Theory to Explore the Concept of Sustainable Development.”, *Futures* 26 (6), pp. 616–25.

-Giampietro, Mario (2003): *Multi-Scale Integrated Analysis of Agro-Ecosystems*, Boca Raton: CRC Press.

-Giampietro, Mario (2019a): “On the Circular Bioeconomy and Decoupling: Implicationsfor Sustainable Growth.”, *Ecological Economics* 162, pp. 143-156.

-Giampietro, Mario (2019b): “The Quality of Scientific Advice for Policy: A Few Insights from Complexity.”, *working paper* del proyecto MAGIC financiado bajo elprograma H2020-GA 689669. Disponible en: https://magic-nexus.eu/sites/default/files/files_documents_repository/quality-scientific-advice- for-policy_magic-report_may2019_0.pdf Consultado el 24 de mayo de 2020.

-Giampietro, Mario; Aspinall, Richard J.;Ramos-Martin, Jesús y Bukkens, Sandra G.F. (2014): *Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use*, New York: Routledge.

-Giampietro, Mario, y Bukkens, Sandra G.F. (2015): “Analogy between Sudoku and the Multi-Scale Integrated Analysis of Societal Metabolism.”, *Ecological Informatics*26, pp. 18-28.

-Giampietro, Mario y Funtowicz, Silvio O. (2020): "From elite folk science to the policy legend of the circular economy", *Environmental Science & Policy* 190, pp. 64-72.

-Giampietro, Mario y Mayumi, Kozo (2010): “Multi-Scale Integrated Assessment of Societal Metabolism: Introducing the Approach.”, *Population and Environment* 22, pp. 109-53.

-Giampietro, Mario y Mayumi, Kozo (2018): "Unraveling the Complexity of the Jevons Paradox: The Link between Innovation, Efficiency, and Sustainability.”, *Frontiers in*

Energy Research 6, pp. 1-13.

-Giampietro, Mario; Mayumi, Kozo y Sorman, Alevgül H. (2012): *The Metabolic Pattern of Societies : Where Economists Fall Short*, New York: Routledge.

-Giampietro, Mario; Mayumi, Kozo y Sorman, Alevgül H. (2013): *Energy Analisys for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism,* New York: Routledge.

-Giampietro, Mario y Renner, Ansel (2020): "The Generation of Meaning and preservation of Identity in Complex Adaptive Systems-The LIPHE4 Criteria". En *Proceedings of the "Tenth International Conference on Complex Systems",* Nashua: Springer-Verlag.

-Haberl, Helmut; Wiedenhofer, Dominik; Pauliuk, Stefan; Krausmann, Fridolin; Müller, Daniel B. y Fischer-Kowalski, Marina (2019): "Contributions of Sociometabolic Research to Sustainability Science.", *Nature Sustainability* 2 (3), pp. 173-184.

-Harvey, David (2010): *A Companion to Marx's Capital*, London-New York: Verso.

-Harvey, David (2018): "Universal Alienation.", *Journal for Cultural Research* 22 (2), pp. 137-50.

-Harvey, David (2019): *La Lógica Geográfica Del Capitalismo*. Benach, Núria y Albet, Abel (eds), Barcelona: Icaria editorial.

-Iberall, A.; Soodak, H. y Arensberg, C. (1980): "Homeokinetic Physics of Societies, A New Discipline: Autonomous Groups, Cultures, Polities." En *Perspectives in Biomechanics*, Real, H.; Ghista, D. y Rau, C. (eds), pp. 433-528, New York: Harwood Academic Press.

-Koestler, Arthur (1967):*The Ghost in the Machine*, New York: Macmillan Co.

-Lakoff, George (2010): "Why it Matters How We Frame the Environment.", *Environmental Communication*, 4 (1), pp. 70-81.

-Lotka, Alfred J. (1922): "Contribution to the Energetics of Evolution.", *Proceedings of the National Academy of Sciences* 8 (6), pp. 147-151.

-Luisi, Pier Luigi (2003): "Autopoiesis: A Review and a Reappraisal.", *Die Naturwissenschaften* 90 (2), pp. 49-59.

-Maturana, Humberto y Valera, Francisco (1980): *Autopoiesis and Cognition: The Realization of the Living,* Dordrecht: D. Reidel Publishing.

-McKinnon, Andrew (2010): "Energy and Society: Herbert Spencer's 'Energetic Sociology' of Social Evolution and Beyond.", *Journal of Classical Sociology* 10 (4), pp.

439-55.

-Melgar-Melgar, Rigo E. y Hall, Charles A.S. (2020): "Why Ecological Economics Needs to Return to Its Roots: The Biophysical Foundation of Socio-Economic Systems.", *Ecological Economics* 169, pp. 106567.

-Naredo, José Manuel (1987): *La Economía En Evolución : Historia y Perspectivas de Las Categorías Básicas Del Pensamiento Económico,* Madrid: Siglo XXI, 4ºedición 2015.

-Pattee, H.H. (1995): "Evolving Self-Reference: Matter, Symbols and Semantic Closure.", *Communication and Cognition-Artificial Intelligence* 12 (1-2), pp. 9-27.

-Pirgmaier, Elke y Steinberger, Julia K. (2019): "Roots, Riots and Radical Change-a Road Less Travelled for Ecological Economics.", *Sustainability* 11 (7), 2001. Disponible en: https://www.mdpi.com/2071-1050/11/7/2001 Consultado el 25 demayo de 2020.

-Plumecocq, Gaël (2014): "The second generation of ecological economics: How far has the apple fallen from the tree?, *Ecological Economics* 107, pp.457-468.

-Prigogine, Ilya y Nicolis, Grégoire (1977): *Self-Organization in Nonequillibrium Systems*, New York: Wiley.

-Renner, Ansel; Louie, A.H. y Giampietro, Mario (2020): "Cyborgization of Modern Social-Economic Systems: Accounting for Changes in Metabolic Identity". En *Proceedings of the "Tenth International Conference on Complex Systems",* Nashua: Springer-Verlag.

-Ripa, Maddalena y Giampietro, Mario (2017): "Report on Nexus Security Using Quantitative Story-Telling.", w*orking paper* del proyecto MAGIC financiado bajo el programa H2020-689669.Disponible en: https://magic-nexus.eu/sites/default/files/files_documents_repository/magic-ga689669-d4.1-revision.pdf Consultado el 25 de mayo de 2020.

-Røpke, Inge (2004): "The Early History of Modern Ecological Economics.", *Ecological Economics* 50, pp. 293-314.

-Røpke, Inge (2005): "Trends in de Development of Ecological Economics from the Late1980s to the Erarly 2000s.", *Ecological Economics* 55, pp. 262-290.

-Rosen, Robert (1985): *Anticipatory Systems: Phylosophical, Mathematical and Methodological Foundations,* New York: Pergamon Press.

-Rosen, Robert (2000): *Essays on Life Itself*, New York: Columbia University Press.

-Scheidel, Arnim y Farrell, Katherine N. (2015): "Small-scale cooperative banking and the production of capital: Reflecting on the role of institutional agreements in supporting rural livehood in Kampot, Cambodia", *Ecological Economics* 119, pp.230-240.

-Sorman, Alevgül H. (2015): "Societal Metabolism." En *Degrowth: A Vocabulary for a New Era*, D'Alisa, Giacomo; Demaria, Federico y Kallis, Giorgio (eds), New York: Routledge, pp. 41-44.

-Spash, Clive L. (2015): "The Content, Direction and Philosophy of Ecological Economics." En *Handbook of Ecological Economics*, Martínez-Alier, Joan y Muradian, Roldan (eds), Cheltenham: Edward Elgar Publishing, pp. 26-47.

-Spash, Clive L. (2020): "A Tale of Three Paradigms: Realising the Revolutionary Potential of Ecological Economics.", *Ecological Economics* 169, pp.106518.

-Steffen, Will; Rockström, Johan; Richarson, Katherine; Lenton, Timothy M.; Folke, Carl; Liverman, Diana; Summerhayes, Colin P. et al. (2018): "Trajectories of theEarth System in the Anthropocene.", *PNAS* 115 (33), pp. 8252-8259.

-Tainter, Joseph A. (1988): *The Collapse of Complex Societies*, Cambridge: Cambridge University Press.

-Tainter, Joseph A. (2006): "Social Complexity and Sustainability.", *Ecological Complexity* 3 (2), pp. 91-103.

-Tanuro, Daniel (2020): "El Ecosocialismo Como Imaginario. Nuevos Paradigmas yEstrategias Frente Al Desastre." En Vindel, Jaime (dirección) *Hacia Una Nueva Imaginación Ecosocial. Narrativas y Transiciones Ante La Crisis de Civilización*. Seminario llevado a cabo en Barcelona (5, 6, 7 de marzo de 2020). Disponible en: https://www.macba.cat/es/exposiciones-actividades/actividades/hacia-nueva-imaginacion-ecosocial Consultado el 25 de mayo de 2020.

-Ulanowicz, Robert E. (1986): *Growth and Development: Ecosystem Phenomenology*,New York: Springer-Verlag.

-UN Environment (2019): *Global Environment Outlook (GEO-6): Healthy Planet, Healthy People,* Nairobi. Disponible en: https://wedocs.unep.org/bitstream/handle/20.500.11822/27539/GEO6_2019.pdf?sequence=1&isAllowed=y Consultado el 25 de mayo de 2020.

-Velasco-Fernádez, Raúl; Chen, Lei; Pérez-Sánchez, Laura y Giampietro, Mario (2019):"Multi-scale integrated comparison of the metabolic pattern of EU28 and China in time.", *working paper* del proyecto EUFORIE financiado bajo el programa H2020-

649342. Disponible en: https://sites.utu.fi/euforie/wp-content/uploads/sites/182/2019/05/649342_EUFORIE_D4.4.pdf Consultado el 30 de mayo de 2020.

-Velasco-Fernández, Raúl; Dunlop, Tessa y Giampietro, Mario (2020): "Fallacies ofEnergy Efficiency Indicators: Recognizing the Complexity of the MetabolicPattern of the Economy.", *Energy Policy* 137, pp. 111089. Disponible en: https://www.sciencedirect.com/science/article/pii/S0301421519306767 Consultado el 25 de mayo de 2020.

-Velasco-Fernández, Raúl; Giampietro, Mario y Bukkens, Sandra G.F. (2018): "Analyzing the Energy Performance of Manufacturing across Levels Using the End-Use Matrix.", *Energy*, 161, pp. 559-572.

-Wallace, Rob; Liebman, Alex; Chaves, Luis Fernando y Wallace, Rodrick (2020): "COVID-19 and Circuits of Capital.", *Monthly Review* (May 01, 2020). Disponible en: https://monthlyreview.org/2020/05/01/covid-19-and-circuits-of- capital/ Consultado el 25 de mayo de 2020.

-White, Leslie A. (1943): "Energy and Evolution of Culture." *American Anthropologist* 14, pp. 335-356.

-Zipf, George Kingsley (1941): *National Unity and Disunity: The Nation as a BiosocialOrganism*, Bloomington, IN: Principia Press.

-Zipf, George Kingsley (1949): *Human Behaviour and the Principle of Least Effort: AnIntroduction to Human Ecology*, Cambridge: Addison-Wesley.

Appendix D

Glossary

Autopoietic systems: A class of systems capable of producing themselves as conceptualised by Maturana and Varela. Autopoiesis literally means "self-production" (from the Greek auto for "self" and "poiesis" for "production"). The term autopoiesis describes a fundamental complementarily between structural types and functional types found in biological and social systems.

Benchmark: An indicator that serves as a standard or point of reference by which other quantitative values may be measured or judged. In MuSIASEM, a benchmark is an expected value that describes one of the metabolic characteristics of a known type of socio-ecological system.

Dynamic energy budget: The central idea of the dynamic energy budget concept in MuSIASEM is that any metabolic system has to invest energy in getting energy, but at the same time, it has to invest energy in expressing other behaviours, such as maintaining and updating social institutions in human societies.

Economic labour productivity (ELP): Measures value added per hour of paid work in different functional sectors and calculated as ELP=Gross value added/human activity.

Economic land use productivity (ELUP): Measures value added per hectare in different functional compartments and calculated as ELUP=Gross value added/land use.

Endosomatic energy: Different types of energy inputs, i.e. food items, to support human physiological processes.

Energy carriers: Energy inputs required by the various sectors of society to perform their functions. A society's energy sector produces energy carriers using primary energy sources. Energy carriers include liquid fuels, electricity, and process heat.

Energy throughput: Total energy (endosomatic or exosomatic) required to maintain the societal metabolism for the complete system (total) of a given compartment. It can be provided in any of the semantic categories of accounting.

Exosomatic metabolic density (EMD): Measure the exosomatic energy consumption per hectare of managed land (measured in Joule per hectare). It can be calculated across different hierarchical levels for the various compartments making up a social-economic system. It can be measured in Joule of energy carriers (then it is specific for the category of accounting, e.g. electricity, fuel, process heat) or measured in Joule of gross energy requirement (primary energy equivalent).

Exosomatic metabolic rate (EMR): Measure the exosomatic energy consumption per hour of human activity (measured in Joule per hour). It can be calculated across different hierarchical levels for the various compartments making up a social-economic system. It can be measured in Joule of energy carriers (then it is specific for the category of accounting, e.g. electricity, fuel, process heat) or measured in Joule of gross energy requirement (primary energy equivalent).

Exosomatic energy: Different energy inputs (energy carriers) are converted into end uses where the processes of exergy degradation occur outside the human body but are controlled directly by humans. The exosomatic population (machines and infrastructures) implies that exosomatic energy conversions are a form of metabolism that can no longer directly relate to individuals. Therefore, the exosomatic metabolism should be linked to hierarchical levels and societal compartmentalisation.

Extensive variable: An additive variable useful to quantify a system's size concerning its context and relevant observable quality. More specifically, in natural science, a variable is considered extensive if its values depend on the quantity of substance under study (e.g. volume, entropy, length, etc.).

External End-Use Matrix: A quantitative representation of the metabolic characteristics of the virtual supply systems associated with the production of the imports consumed by a society. These virtual systems' definitions depend on the sets of imported commodities considered and the technical characteristics of the productive processes required to produce them. The matrix characterises the consumption of secondary inputs and societal funds outside the system's borders.

External Environmental Pressure Matrix: A quantitative representation of the primary flows (which need primary supply and primary sink capacity provided by nature) required by technical processes in virtual supply systems to produce the imports outside the system's borders.

Externalisation: The entangled social, economic and environmental effects resulting from displacing extractive and productive industries outside of governance boundaries (regional, national or supranational). Externalisation plays a crucial role in relaxing the constraints imposed on the local combination of production processes about viability (internal constraints) and environmental feasibility (external constraints determined by biophysical processes outside human control).

Flow-Fund model for metabolic systems: Georgescu-Roegen proposed a flow-fund model to represent the metabolism of social-economic systems. Fund elements are elements whose identity remains "the same" during the analytical representation, i.e. they reflect the choice made by the analyst when deciding "what the system is" and "what the system is made of". They are the elements in charge of the metabolism of social-economic systems, transforming input flows into outflows. Examples of fund elements are capital, people and colonised land. In turn, flow elements disappear and appear throughout the representation. They reflect the choice made by the analyst when deciding "what the system does" or how it interacts with its context. Examples of flow elements are fossil fuels, food, or waste generated in industrial processes.

Functional type: A functional type is related to a large-scale view. It refers to the role of a particular component expected to be fulfilled within a given associative context to which it belongs. Such a role emerges from the question of why this component is necessary.

Gross energy requirement (GER): A virtual quantity of thermal energy calculated using the partial substitution method to assess the total energy throughput of a society.

Gross value added (GVA): A measure of the economic value of goods and services produced in an economy's area, industry or sector. It equals production minus intermediate consumption.

Human activity (HA): The fund element required for controlling the generation and the effective delivery of applied power generated by exosomatic devices. Human activity (a proxy of the presence of humans in the functional compartment considered) at the local scale is measured in hours (per year). When accounted for within the compartments belonging to the paid work sector, it is also referred to as human labour.

Impredicative: In an impredicative analysis, the results are contingent and context-dependent. We can say that impredicativity is related to a dialectical process of interaction and co-evolution between the whole and the parts. For this reason, impredicativity conflicts profoundly with the simplifications inherent in reductionism and challenges the unidirectional explanation of causality. Impredicativity is a typical attribute of complex autopoietic systems.

Intensive variable: A non-additive variable valid to quantify a relevant quality of a system, which must be expressed homogeneously over the whole system per unit of size. More specifically, in natural science, an intensive variable is independent of the quantity of material present (e.g. density, pressure, temperature, etc.).

Internal End-Use Matrix: A quantitative representation of the metabolic characteristics of the actual "internal supply systems" (a specific set of productive processes required to produce the given supply of commodities inside the system's border) associated with making the goods and services consumed by society.

Internal Environmental Pressure Matrix: A quantitative representation of the primary flows (which require primary supply and primary sink capacity provided by nature) exchanged by technical processes inside the system's borders associated with producing the goods and services consumed by society.

Land use (LU): Hectares of land included in one of the categories used for managing land. It represents the social and economic functions and purposes of land.

Metabolic pattern This term refers to all energy and material transformations occurring within an open social system and between it and its environment.

Metabolic processor: A term derived from relational biology. They have the peculiar ability to combine data from different dimensions in a coherent pattern that is non-reducible to each other (e.g. data from different dimensions). Metabolic processors are used to characterise the metabolic characteristics of both structural (characterised using bottom-up information) and functional (characterised using top-down information) components of the metabolic network.

Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM): A semantically open accounting framework belonging to sociometabolic research based on integrating conceptual insights from various disciplinary domains belonging to what has been called complexity science.

MuSIASEM toolkit: A set of analytical tools based on the MuSIASEM accounting framework used to integrate the characterisation referring to various levels of analysis required to identify and study relevant attributes of metabolic patterns.

Partial substitution method: This method boils down to the accounting of virtual quantities (in Joule) of primary energy source equivalent (thermal energy form such as tonnes of oil equivalent) per each joule of vis electrica (a form of mechanical energy). In MuSIASEM, the method of calculating the gross energy requirements not only considers the losses for generating electricity (2.61) but also accounts for the losses for obtaining fuels (1.38) and heat (1.1).

Post-normal science: It is an expression proposed by Silvio Funtowicz and Jerome Ravetz to indicate a critical situation in the production and use of science for governance. In contrast with the situation of “normal science”, as defined by Kuhn, a post-normal science situation indicates that “facts are uncertain, values in dispute, stakes high and decisions urgent”. This implies changing the focus of the discussion from truth to quality by enlarging the variety of methods, criteria and actors involved in assessing the validity and relevance of the scientific output.

Primary energy sources (PES): Refers to the energy forms required by the energy sector to generate the supply of energy carriers used by human society. According to the laws of thermodynamics, primary energy sources cannot be produced. They must be available to society to make the production of energy carriers possible. Primary energy sources include below-ground fossil energy reserves (coal, gas, oil), blowing wind, falling water, sun and biomass.

Social-Ecological System (SES): A complex of functional and structural elements combined in constituent components, operating within a prescribed boundary that is controlled and determined by the activities expressed by a given set of ecosystems (in the ecosphere) and a given set of social actors and institutions (in the anthroposphere).

Structural type: A structural type is related to a local scale view. It defines the characteristics of an equivalence class of organised structures mapping onto a particular template. Realisations of these structural types can express expected features (behaviours). Therefore, an instance of a structural type belonging to a network must be able to process a particular set of inputs and deliver a specific set of outputs at the speed expected by the rest of the network.

Water Metabolic Density (WMD): A measure of the water consumption per hectare of human activity within a societal compartment. It can be calculated across different hierarchical levels for the various social-economic system compartments.

Water Metabolic Rate (WMR): A measure of the water consumption per hour of human activity within a societal compartment. It can be calculated across different hierarchical levels for the various compartments making up a social-economic system.

Water Throughput (WT): Total water required to maintain the societal metabolism for the complete system (the whole) or a given compartment. It can be provided in any of the semantic categories of accounting.