Island-based Polygeneration Systems

Feasibility of Biomass-driven Distributed Concepts

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Doctoral Thesis

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Abstract

The colossal risks and challenges posed by climate change require innovative solutions that must fulfil energy service demands sustainably. The concept of small-scale, biomass-based polygeneration (SBP) is one such technological approach, which optimizes locally supplied fuels to provide several energy services like electricity, heating, cooling, potable water, and/or bio-chemical products. By presenting chosen SBP systems and models employed in various socio-geographic locations, in particular distributed applications, the thesis identifies benefits as well as drawbacks of the SBP concept and aims to promote its wider usage in the field.

Because a multitude of technologies can be applied for polygeneration system design, the thesis starts with a thorough review of the highly complex and rapidly evolving field, where relevant literature is presented and assimilated. Based on this review, several models have been created for various solar-assisted SBP systems: Firstly, a small-scale Combined Cooling, Heating, and Power (CCHP) system based on biomass gasification has been investigated for a hotel resort on one of the Andaman Islands, India. Apart from economic and environmental superiority compared to a fossil-fuel reference system, the study also expanded technological aspects by adding a socio-political analysis of the benefits and drawbacks of the system for the entire island community. In the second study, a novel control algorithm was devised for a biogas-based polygeneration system generating electricity and potable water generation for a rural off-grid village in El Pando, Bolivia. It was found that the proposed system could lead to significant cost and emissions reductions paired with greater energy autonomy. In the third study, an optimization model for a combined gasification-based CCHP/Heat Pump (HP) system is presented for a tourist facility in Barcelona considering various climate scenarios. The study reveals that the system design is only slightly affected by future changes in climate and that the CCHP/HP system shows only a moderate economic performance but still considerable CO_2-savings potential.

The overall findings of these studies reveal that the economic feasibility of SBP systems depends greatly not just on their inherent design but also on their location. However, all proposed polygeneration systems could lower emissions significantly, while excelling in energy efficiency as well as adaptability towards service demands and other technologies. The presented studies contribute to the state of the art by adding innovative polygeneration system designs, proposing new modelling approaches and subsequent models including SBP system enhancing technologies, as well as by investigating the effects of geographical location and climate change on the system design process.

Sammanfattning

Klimatförändringen bär med sig kolossala risker och utmaningar, som kräver innovativa lösningar för att tillhandahålla energitjänster på ett mer hållbart sätt än med tidigare energisystem. Konceptet med småskaliga, biomassa-baserade polygeneration (SBP) system är ett sådant teknologiskt tillvägagångssätt, vilket optimerar användningen av lokalt producerat bränsle för att tillhandahålla olika energitjänster som elektricitet, värma, kyla, dricksvatten, eller/och bio-kemiska produkter. Doktorsarbetet identifierar för- och nackdelar hos olika SBP konceptet genom att presentera ett urval av SBP system och modeller av dem för olika geografiska regioner, med mål att främja vidare applikation av dem i fält.

Eftersom en mängd tekniker kan användas för design av polygenerationssystem, börjar avhandlingen med en grundlig genomgång av det mycket komplexa och snabbt utvecklande området, där relevant litteratur presenteras och assimileras. Baserat på denna recension har flera modeller skapats för olika solassisterade SBP-system: För det första har ett småskaligt kombinerat kyl-, värme- och kraftsystem (CCHP) baserat på biomassaförgasning undersökts för en hotellanläggning på en av Andamanöarna, Indien. Bortsett från ekonomisk och miljömässig överlägsenhet jämfört med ett referenssystem för fossila bränslen har studien även inkluderat tekniska aspekter genom att lägga till en socio-politisk analys av fördelarna och nackdelarna med systemet för hela ö-samhället. I den andra studien utvecklades en ny regleralgoritm för ett biogasbaserat polygenereringssystem som genererar el och renar vatten till dricksvatten för en by utan elförsörjning i El Pando, Bolivia. Det konstaterades att det föreslagna systemet kan leda till betydande kostnads- och utsläppsminskningar i kombination med större energiautonomi. I den tredje studien presenteras en optimeringsmodell för ett kombinerat förgasningsbaserat CCHP / värmepumpsystem (HP) för en turistanläggning i Barcelona under olika klimatscenarier. Studien avslöjar att systemdesignen bara i låg grad påverkas av framtida klimatförändringar och att CCHP / HP-systemet endast visar en måttlig ekonomisk prestanda men fortfarande en betydande potential för CO2-besparingar.

De övergripande resultaten av dessa studier visar att den ekonomiska genomförbarheten för SBP-system inte bara beror på deras inneboende design utan också på deras lokalisering. Alla föreslagna SBP-system kan emellertid sänka emissionerna betydligt, samtidigt som de sticker ut i energieffektivitet samt anpassningsbarhet efter energitjänster och annan teknik. De presenterade studierna bidrar till vetenskapen genom att lägga till innovativa SBP-systemdesigner, föreslå nya modelleringsmetoder och efterföljande modeller inklusive SBP-systemförbättrande teknik, samt genom att undersöka effekterna av geografisk plats och klimatförändringar på systemdesignprocessen.

Resumen

Los colosales riesgos y retos puestos por el cambio climático requieren soluciones creativas para satisfacer las demandas de servicios energéticos de una manera más sostenible, comparado con los sistemas actuales. El concepto de poligeneración a escala pequeña y basada en biomasa (Small-scale, biomass-based polygeneration o SBP) es uno de estos enfoques, que optimiza el uso de combustible locales para proveer varios servicios energéticos como electricidad, calor, enfriamiento, agua potable y/o productos bioquímicos. Presentando una selección de sistemas SBP y modelos empleados en varias localizaciones socio-geográficas, esta tesis identifica los beneficios e inconvenientes del concepto SBP con el objetivo de promover ~~su~~ un uso más amplio en el mundo.

Como se puede aplicar una multitud de tecnologías para el diseño de sistemas SBP, la tesis empieza con una revisión profunda del campo, altamente complejo y dinámico, donde la literatura relevante está presentada en una forma estructurada y resumida. Basado en esta revisión, se han creado varios modelos SBP para varios sistemas SBP con asistencia solar: Principalmente, se ha investigado un sistema de generación conjunta de frio, calor y electricidad (en inglés: Combined Cooling, Heating, and Power or CCHP) basado en gasificación de biomasa para un resort (hotelero) en una de las islas Andamán, India. Además de mostrar de una superioridad económica y ambiental comparado con el sistema de referencia de combustibles fósiles, el estudio expandió el conocimiento científico añadiendo un análisis socio-político de los beneficios e inconvenientes del sistema SBP para la comunidad de la isla entera. En el segundo estudio, se ha desarrollado un nuevo algoritmo de control para un sistema de poligeneración basado en biogás, que genera electricidad y agua potable para una comunidad rural y sin conexión a una red eléctrica más grande en el Pando, Bolivia. Se ha revelado que el sistema propuesto podría bajar significantemente los costes y las emisiones junto con un aumento de la autonomía energética. En el tercer estudio se ha presentado un modelo de optimización para un sistema combinado de CCHP y bombas de calor (sistema CCHP/HP), que se considera para una estructura museístico-turística en Barcelona y para varios escenarios climáticos. En el estudio se ha descubierto que el cambio climático influye sólo ligeramente en el diseño del sistema óptimo, y que el sistema CCHP/HP demuestra sólo un moderado desempeño económico, similar al convencional, pero también un potencial considerable para la reducción de emisiones de CO_2.

El conjunto de los estudios revela que la viabilidad económica de los sistemas SBP depende altamente no solo de su diseño inherente, sino también de su entorno. De todos modos, todos los sistemas SBP propuestos podrían bajar las emisiones significantemente, mientras sobresalen en eficiencia energética y adaptabilidad a servicios energéticos y tecnologías alternativas. Los estudios presentados contribuyen al estado del arte añadiendo diseños innovadores de sistemas SBP, proponiendo nuevos enfoques de modelado y cálculo, y subsecuentemente nuevos modelos incluyendo tecnologías aumentando sistemas SBP, e investigando los efectos de la ubicación geográfica y del cambio climático al proceso del diseño de los sistemas SBP.

Preface

This doctoral thesis was completed at the division for Architecture, Energy, and Environment (AIEM) at the Polytechnic University of Catalonia (UPC), Barcelona, and at the division of Heat and Power Technology (HPT) in the department of Energy Technology (EGI) at KTH Royal Institute of Technology (KTH), Stockholm. The PhD project was conducted in the framework of the SELECT+ Doctoral Program (Environomical Pathways for Sustainable Energy Services), financed by the EACEA (Education, Audiovisual and Culture Executive Agency). The research was conducted under the supervision of Professor Antonio Isalgué (UPC), Associate Professor Anders Malmquist (KTH) and Professor Andrew Read Martin (KTH). During the PhD project, an industrial placement was arranged with the energy consulting company Aiguasol Coop located in Barcelona, which was financially supported by the InnoEnergy PhD School.

In this thesis, the topic of small-scale, biomass-based polygeneration systems is explored from a scientific but also from a practical engineering perspective. Several polygeneration system modelling approaches and models are presented, which allow for the optimization of SBP system designs and for analysing their economic, energetic, and environmental performance. This thesis is based on a compilation of several research papers including their methodologies, case studies and main findings. By putting all these studies into the greater research context of the PhD project, the synthesis of these research papers provides a comprehensive and detailed portrayal of the topic. The aforementioned papers can be found in the Appendix.

Appended publications

List of appended publications

PAPER I

Wegener M, Malmquist A, Isalgué A, Martin A. Biomass-fired combined cooling, heating and power for small scale applications – A review. Renew Sustain Energy Rev 2018;96:392–410. doi:10.1016/j.rser.2018.07.044.

Paper II

Wegener M, Isalgué A, Malmquist A, Martin A. 3E-Analysis of a Bio-Solar CCHP System for the Andaman Islands, India—A Case Study. Energies 2019;12:1113. doi:10.3390/en12061113.

PAPER III

Wegener M, Villarroel-Schneider J, Malmquist A, Isalgue A, Martin A, Martin V. Techno-economic optimization model for polygeneration hybrid energy storage systems using biogas and batteries – SUBMITTED TO Energy 2020;TBD.

PAPER IV

Wegener M, Malmquist A, Isalgue A, Martin A, Arranz P, Camara O, et al. A techno-economic optimization model of a biomass-based CCHP/heat pump system under evolving climate conditions. Energy Convers Manag 2020;223:113256. doi:10.1016/j.enconman.2020.113256.

PAPER V

Wegener M, Malmquist A, Isalgue A, Martin A, Santarelli M, Arranz P. Exergetic analysis of a small-scale CCHP&HP system based on biomass gasification. Internal Revision 2020.

Other publications

Wegener M, Zhang Y, Isalgue A, Malmquist A. Economic and Ecologic Assessment of a Biomass-Based CHP System for a Hotel Resort on the Andaman Islands, India. World Renew. Energy Congr. 2018, Springer, Cham; 2020, p. 889–98. doi:10.1007/978-3-030-18488-9_74.

Herrera I, Rojas A, Villardefrancos FL, Malmquist A, Wegener M. Analysis for the integration of solar energy to sugarcane bagasse cogeneration power plant in the Cuban context : a case study. Proc. ECOS 2019 - 32ND Int. Conf. Effic. COST, Optim. Simul. Environ. IMPACT ENERGY Syst., 2019.

Wegener M, Isalgué Buxeda A, Malmquist A, Herrera I. Sistemas de poligeneración en el ámbito urbano: ventajas e inconvenientes en la actualidad. Int Conf Virtual City Territ 2019;13. doi:10.5821/ctv.8536.

Wegener M, Ordóñez CL, Isalgué A, Malmquist A, Martin A. How Much Does It Cost to Go Off-Grid with Renewables? A Case Study of a Polygeneration System for a Neighbourhood in Hermosillo, Mexico. In: J.Littlewood, R.J.Howlett AC and LCJ, editor. Sustain. Energy Build., Budapest, Hungary: Springer; 2019, p. 395–405. doi:10.1007/978-981-32-9868-2_34.

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Contents

Table of Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

3E	Energetic, Enviromental, and Economic
ABS	Absorption Chiller
ASHP	Air-sourced Heat Pumps
BCHP	Building Cooling, Heat, and Power
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DHW	Domestic Hot Water
DM	Demand Model
EA	Evolutionary Algorithm
EM	Economic Model
ER	Equivalence Ratio

EER	Energy Efficiency Ratio
FC	Fuel Cell
FEL	Following Electric Load
FTL	Following Thermal Load
GA	Genetic Algorithm
GHG	Greenhouse Gases
GSHP	Ground-sourced Heat Pumps
HESS	Hybrid Energy Storage System
HEx	Heat Exchanger
HP	Heat pumps
ICE	Internal Combustion Engine
LCOE	Levelized Cost Of Energy
LHV	Lower Heating Value
LP	Linear Programming
MCCHP/ µCCHP	Micro CCHP (< 20 kW_e)
MILP	Mixed-Integer Linear Programming
MILNP	Mixed-Integer Non-linear Programming
NPC	Net Present Cost
ORC	Organic Rankine Cycle
PSO	Particle Swarm Optimization
PV	Photovoltaic
PVT	Photovoltaic-Thermal
RES	Renewable Energy Sources
RO	Reverse Osmosis
SBP	Small-scale Biomass-based Polygeneration
SM	Supply Model
VC	Vapour Compression Chiller

Symbols for physical parameters

C_p	Specific heat capacity with constant pressure [kJ/(kg·K)]
e	Specific exergy [kJ/kg]
E	Energy [kJ or kWh]
h	specific enthalpy [kJ/kg]
LHV	Lower Heating Value [kJ/kg]
m	mass flow [kg/s]
R	universal gas constant [8.3145 kJ/(kg·K)]
T	Temperature [K]
Q	Thermal energy [kW]
w	mass fraction
W	Work [kW] (used as equal to Electric Energy)
y	molar fraction
m/p/q/r/s	Variables for relative atomic structure
x_i	Variables for amounts of molecules

Symbols for economic parameters

R_t	Cashflow for year t
$C_{ann,tot}$	Annualized Costs
i	Real discount rate
j	Component index
CC_j	Capital cost for component j
RC_j	Replacement cost for component j
OM_j	Cost and revenues for operation & maintenance for component j
FC_j	Fuel cost for component j
SR_j	Salvage revenues for component j

Subscripts

c	cooling
ch	chemical
cs	capacity shortage
e	electric
g	gaseous
h	heating
i	numeration index
l	liquid
max	maximum
ph	physical
o	Reference state
th	thermal

1. Introduction

For several decades the scientific community has been warning of the consequences of greenhouse gas (GHG) emissions on global climate and subsequently on the socio-economic implications for humankind [1]. Meteorological phenomena of climate change include amongst others [2]: more extreme weather events (e.g. hurricanes, heat waves, droughts, etc.), rising global average temperatures of sea, land, and air temperatures, less predictable climate patterns on regional levels, rising sea levels, etc.. All these phenomena have in turn direct effects on all regions of the world and all living beings including humans and various habitats. These effects are interconnected and can be mutually reinforcing including threats like changing patterns in agriculture [3], loss of habitable regions [4], risk of losing fresh water supplies [3], loss of biodiversity [5], direct loss of human lives due to natural catastrophes, starving, and new distribution patterns of diseases [6].

By now, the scientists' warnings have been heard by powerful stake holders within industry, politics, research, and society, but the current challenges and the future risks remain colossal. In this context, the energy sector has been identified as crucial for the 21st century energy transition towards a more sustainable and less polluting society [7,8]. Nonetheless, global primary energy consumption is still dominated by fossil fuels like oil, coal, and natural gas as shown in Figure 1. Moreover, for electricity generation, these fossil fuels are often burned in large, centralized power plants far away from the final consumer. These remote power plants have considerable drawbacks [9]: electricity transmission losses, heat transmission losses, little modularity, less grid stability, and dependence on singular, often imported energy resources.

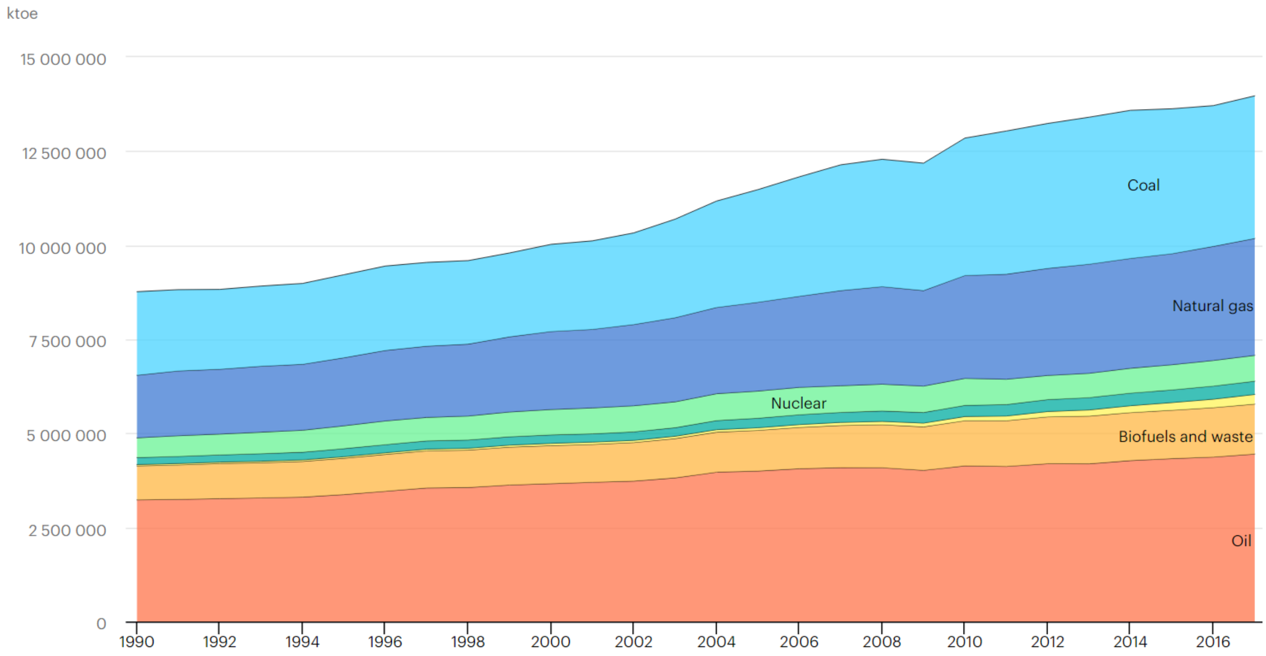


Figure 1 Worldwide Total primary energy supply by source [10]

Today's energy systems and especially electricity systems are moving away from centralized fossil-fuel power plants towards distributed, modular units powered by renewable resources [11]. However, although wind and photovoltaic (PV) solar systems have seen immense investment and capacity growth, they focus primarily on serving electric power, while this represent only a small part of final energy use. For example, as shown in Figure 2, in the residential sector of EU countries purely electric appliances make up less than 15% of final energy use while thermal services like space heating or cooling represent more than 64% [12]. Additionally, the volatile nature of energy sources like wind and PV hinders them from becoming universal solutions for the energy transition, unless back-up energy resources and/or sufficient energy storage are considered [13].

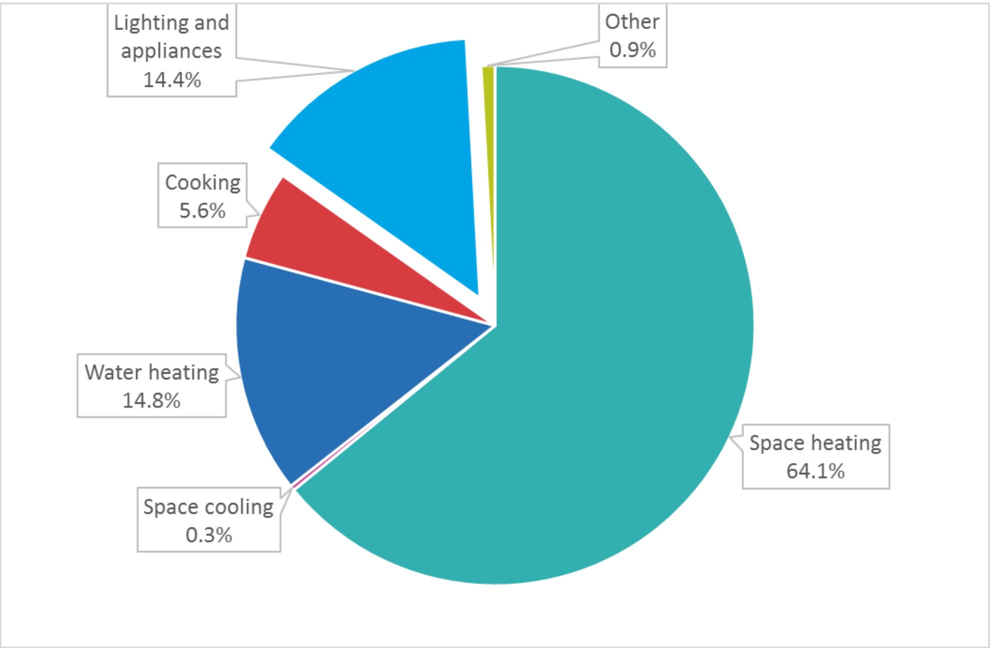


Figure 2 Final energy consumption in the residential sector by use, EU-28, 2017 [12]

The concept of small-scale polygeneration tackles the previously mentioned issues by providing not just electricity but also additional energy services for local communities and consumers [14,15]. Already the earliest commercial power plants were constructed as cogeneration plants with the aim to sell not just electricity but also steam generated using the combustion exhaust heat [16]. Further elaboration of this idea led to the concept of polygeneration systems with the objective of transforming any given number of natural resources as efficiently as possible to a selection of energy services and products. As shown in Figure 3, a wide variety of natural resources, ranging from low-exergy components (e.g. untreated seawater) to high-exergy components (e.g. hydrogen), can be considered. Similarly, a multitude of energy services can be provided by a polygeneration system including direct energy services like electricity but also portable products like fuels or potable water.

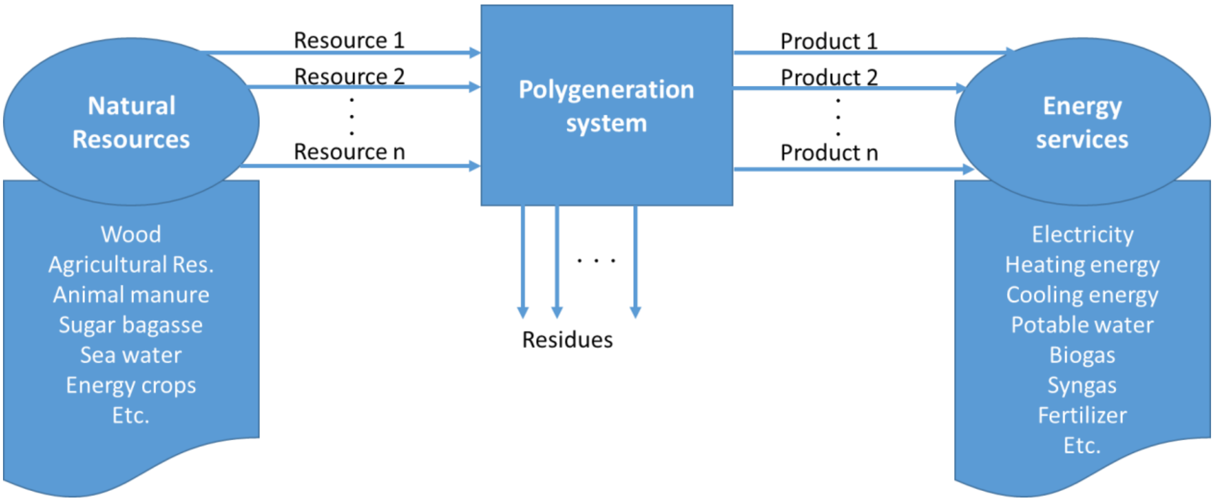


Figure 3 Polygeneration concept: multi-resource transformation to multi-products [17]

Although small-scale polygeneration systems can be fuelled with fossil fuels, such systems would not represent a sustainable solution but only a less polluting form of energy service provision. However, when using bio-resources instead, the concept of small-scale biomass-based polygeneration (SBP) systems can distinguish itself from conventional energy systems with various favourable characteristics:

- **High Efficiency** [18]: The major objective of the polygeneration concept is to capitalize on the primary energy resource as efficiently as possible. By providing several energy services in close proximity to the final consumer, well-designed polygeneration systems reach generally much higher overall energetic efficiencies than conventional, centralized systems.
- **Renewable** [19,20]: SBP systems can represent a renewable source of energy provision, but only when supplied with biomass resources harvested under sustainable management regimes. Over a certain life cycle, the biomass will regrow and absorb the emissions caused by combustion within the polygeneration system. Hence the system would operate carbon-neutrally. This is especially true for second and third generation fuels, which are based on by-products from agriculture or forestry.
- **Flexibility** [21]: Depending on the technologies incorporated, polygenration systems can provide various services with great flexibility. This ability is especially desirable on islands and in rural areas, where no alternative energy service providers may be available.
- **Combinability** [9,22]: Although SBP systems can serve demands with considerable flexibility, they may be strictly limited by the biomass resources available or their economic viability may be reduced due to high biomass prices. However, SBP systems can be coupled easily with other energy resource technologies (e.g. solar), other storage technologies (e.g. batteries), or other energy efficiency technologies (e.g. heat pumps (HP)). This in turn, may not only lead to higher maximum capacities, but also to a more stable and secure overall system with less risk of total breakdown.
- **Local Resources** [20,23]: While in most regions the supply of fossil fuels depends on external sources, for SBP systems locally grown and harvested biomass can be used. In consequence, local supply chains as well as jobs can be created and the local energy autonomy can be increased.
- **Resilience** [24]: SBP systems can increase grid resilience not just by lowering the dependence of one consumer structure on the grid but also by possibly providing

energy services to the entire network. The SBP system could turn the final consumer to a combination of consumer and producer, often referred to as prosumer [25].

The many advantages show clearly that SBP systems have potential to play an important role in the 21st century energy transition. However, there are also certain drawbacks inherent to the concept of SBP. Firstly, due to their individual nature and the necessity to adjust each system to the consumer's demand, the design of polygeneration systems is immensely complex [19]. From this complexity stems also uncertainty, as several technologies have to work together within uniquely designed systems, which may lead to unforeseen technical issues. This does not just slow down the technical conception of SBP systems, but also complicates the financing processes as it requires more time to convince investors. Additionally, once the system has been constructed skilled technicians are required for secure maintenance and operation. Secondly, although biomass can be collected to a certain degree in almost every habitable region, it often may still not be enough to fulfil energy demands even with the most efficient polygeneration design. This is especially critical in urban areas or densely populated islands [26]. Hence, just as with wind and solar technologies, SBP should not be regarded as a universal solution for a more sustainable energy system. The questions arises, when and where SBP systems can reach their full potential and outperform not just conventional but also new alternative energy technologies.

Within the greater context of the energy transition, there are several other technologies competing with the concept of SBP, ranging from micro-scale solar PV systems to large-scale energy network management technologies. Although many of these technologies are compatible with SBP systems, they may be favoured by investors without considering polygeneration due to possible smaller capital cost or simpler technical implementation. Additionally, energy-related technologies are advancing at a rapid pace transforming economic markets, politics, and societal structures [27]. As the SBP concept consists of various technologies, the concept itself is also changing dynamically with new engineering and design ideas appearing constantly. This further increases uncertainty and calls for a cohesive overview of available technologies and concepts in order to allow scientists, engineers, investors, and policy makers to make the right decisions.

Even if the choice of technologies to be considered has been narrowed down, the necessary sizing of system components is crucial for technical and economic performance. To answer this question, firstly, thorough analyses of the desired services and demands as well as of the available local resources are necessary [28]. Based on these analyses, several techniques and tools to engineer a suitable SBP systems can be used ranging from experimental trial-and-error approaches to complex optimization algorithms [29,30]. However, some of these techniques may not be suitable for brand-new polygeneration systems that have never been conceived before. This implies that it may be necessary to develop further design techniques and computational tools for SBP system engineering in order to expand their potential application and increase precision of their techno-economic analyses.

1.1.Research questions

This thesis aims to respond to some of the previously raised issues and challenges concerning the concept of SBP systems. To this purpose, several studies on various aspects of SBP systems have been conducted, which in their compilation answer or at least reveal insights to several unresolved questions. The general questions guiding this thesis are the following:

1. **Where and how can SBP systems be an economically feasible alternative to currently established energy systems?**
2. **How do these SBP systems perform compared to other energy systems in terms of energetic and environmental benefits?**

Related to the first question, the currently used energy system will be specified as the reference system for each study. In most cases, the reference energy system is a conventional fossil-fuel based, single generation system. In context of these general research questions, several more specific questions arise, which were the focus of one or several of the papers published during the PhD project. Table 1 lists these questions and relates each questions to the corresponding publication.

Table 1 List of specific research questions answered in the thesis

What are suitable parameters to analyse the energetic, environmental, and economic (3E) performance of SBP systems and to compare such systems to conventional ones?	PAPER I
Which technologies are currently used in SBP systems? Which technologies are to be expected in the near future?	PAPER I
What are optimal methods to design and operate SBP system?	PAPER II - PAPER V
How do SBP systems interact with alternative technologies	PAPER III & IV

Hence, the general objectives of this work are to summarize all current knowledge on SBP, highlight undiscovered research paths, and expand the knowledge on SBP systems within the greater context of the 21st century energy transition. By answering above questions, this study does not just advance the academic knowledge on SBP systems, but does also facilitate the design of SBP systems for engineers and technicians, while highlighting distinctive beneficial as well as unfavourable features.

1.2. Technological scope of the study

While the concept of polygeneration is not only gaining increasing interest amongst scientists and engineers, it also describes a plethora of combinable technologies. In consequence, the amount of literature and studies on systems, which would fit the broader definition of polygeneration systems, exceeds the reasonable framework of a PhD thesis. Hence, it is necessary to limit the scope of this study and to locate its importance within the field of energy technologies. For this thesis, the following technological scope on the studied polygeneration systems has been set:

- **Small-scale:** All studied systems are small-scale energy systems, which is defined here as systems with less than 1 MW rated electricity output [31]. Exemplary client structures for which these SBP systems would be suitable are supermarkets, hospitals, schools, office buildings, but also small villages, neighbourhoods, and/or islands.
- **Biomass-based:** The concept of polygeneration can be and is frequently based on the combustion of fossil fuels. However, considering that this thesis is put into the greater framework of the 21st century energy transition, the focus has been laid on

sustainable energy resources. Amongst renewable energy sources (RES), biomass is just one of many resources, but it is arguably one of the most universally applicable candidates for renewable energy-based, small-scale polygeneration systems. For example, the rapidly growing wind and PV technologies are not generating heat at high enough temperatures for most polygeneration concepts, while they are also suffering from high intermittency [32]. On the other hand, geothermal energy might generate heat at sufficiently high temperatures, but is too locally limited to be considered a globally applicable solution [33]. Using solar-thermal energy collectors for small-scale electricity and heat generation seems to be a promising solutions, especially in conjunction with organic Rankine cycle (ORC) and Stirling engines. However, so far only few of these system concepts are market ready as reliability and maintenance have still to be improved [34]. Hence one of the great advantages of biomass is that it can be produced, harvested, stored, and used as a fuel in most habitable regions making it a flexible alternative to fossil fuels [35]. However, there are also many cases where biomass is in disfavour compared to other technologies, especially in regions with limited or no biomass growth (e.g. arid regions, tundra regions, and regions suffering from excessive deforestation). Hence, biomass is also not a universal solution, but is in the majority of cases a very suitable candidate for renewable energy polygeneration systems.

- **Island-based / Autonomy:** Especially for island-based and rural systems in developing countries, a connection to a larger electric grid would imply infeasible connections costs. However, even for systems studied in urban locations with good access to a large electric grid, entirely autonomous operation with no electricity served by the grid was studied for all conceived systems. This mode of operation is generally referred to as island-mode [36,37] and the entire thesis concentrates on such island-based systems.
- **CCHP and water purification:** The thesis concentrates on advanced small-scale polygeneration systems beyond the concept of combined heat and power (CHP). Hence, heat recovery is essential in all studied systems, but is always followed by another conversion process, more specifically either heat-driven cooling or water purification to increase the number of energy services provided minimal increase on electricity demand. In some cases, both electricity- and thermal-driven cooling technologies are considered and their collaboration is investigated. While these two aforementioned conversion processes already imply the knowledge of an ample set of technologies, this definition excludes various other fields of energy technologies, most notably biofuel generation. There are two major reasons for excluding the generation of biofuels from the focus of this study. Firstly, the energy systems are designed to satisfy the demand of a set local structure, hence there is no need to export any fuels. Secondly, the generation of high quality fuels at the small-scale level would rarely be an economically reasonable solution.
- **Solar-power enhanced:** Despite of the great advantage of biomass as being a storable energy resource, it is also limited in its biomass production capacity of the surroundings. Hence, for many systems it is necessary to enhance the SBP system with an additional energy source. This reduces dependence on one single energy source by forming a hybrid energy system. In all studied systems, PV power has been considered as a flexible and easily scalable additional RES.
- **Storage technologies:** In relation to additional solar power technologies, in many studied systems other forms of energy storage apart from biomass have been considered in order to maximise the utilization of the biomass resources. Hence, not just hybrid energy sources but also hybrid energy storage systems (HESS) have been

designed, specifically batteries, biogas storage domes, and water tanks for heat and cooling storage. Such HESS may lead to greater system flexibility, longer lifetimes and better economic performance [38].
- **By-products:** Although the generation of electric and thermal energy services are the main technical objectives of each system, in some studies additional bio-chemical by-products and their greater socio-economic importance are considered. A typical by-product for systems based on gasification would be charcoal, while for systems based on anaerobic digestions a typical by-product would be bio-slurry.

1.3. Limitations

Apart from the limitations determined by the technological scope of the study as outlaid in Chapter 1.2, there are also multiple methodological limitations to be acknowledged for this thesis. These limitations have direct impact on how this thesis addresses the research questions raised in 1.1:

- **Data quality:** All results of the presented studies are based on data gathered from external scientific, commercial, and governmental sources. All values and all sources obtained from these sources have been examined, chosen, and referenced with great care. Nevertheless, many implicit assumptions were inevitably made. For example, data from a few years ago or from specific regions may no longer represent current realities, especially for economic variables for rapidly developing markets.
- **Technical system perspective vs. political environment:** All systems have been investigated and designed from the perspectives of the polygeneration system owner and/or operator. Even if the data would be 100% precise for a given moment and a given location, it still remains highly influenced by circumstances outside of the control sphere of the technical system. Unforeseeable changes in political frameworks could quickly reduce the accuracy of the economic results. The political environment influences economic input variables (e.g. biomass prices) as well as output variables (e.g. electricity sales price). This dependence on political circumstances also affects directly the environmental analysis of the studied systems, especially the sustainability of the provided biomass. Although the biomass provision partners should be chosen with due diligence, the administrative and political structures behind the biomass provider are primarily responsible for upholding the legal standards of sustainability-related regulations.
- **Computational limitations:** For all presented model studies, a brute force optimization approach has been chosen, wherein several size iterations for various components of a proposed polygeneration system are simulated. Although such a brute-force approach may find the best solution given the provided search space and search steps, it is also the most exhaustive method and hence requires the longest computation time [39]. In order to reduce computation time, the search steps can be enlarged (i.e. consider larger differences between considered component sizes) but this would lead to less precise results.
- **Sample size for trend analysis:** Based on the published studies presented in chapters 3 and 4, some trends are eventually identified and discussed in Chapter 5. It must be noted that the identification of these trends is based on a very small number of studies and can therefore not be considered as scientific proof but instead should be regarded as anticipatory indications.

Some of these limitations and their implications for this as well as for future studies are discussed in more detail in Chapter 5 after the presentation of the different publications of which this thesis is composed of.

1.4. Structure of the thesis

As mentioned in Chapter 1.2, this thesis is based on several published or to-be-published scientific papers. Hence this thesis aims to collect and summarize the findings of all papers presenting them in a coherent and concise way. To this purpose the thesis is structured as follows:

1. In the introduction of Chapter 1, the motivation and the objectives are presented. In order to not exceed the framework of this thesis, some technological limits have been set for the scope of the study. In Chapter 1.3, the major methodological limitations of this thesis are defined.
2. In Chapter 2 the methodological frameworks used for each study and for the entire thesis are presented. The selected computational tools are presented and briefly evaluated. Some key formulae and parameters are given and defined.
3. The state of the art on SBP is presented in Chapter 3. This chapter starts by putting the thesis into the general context of biomass and distributed energy systems. Then, specific studies on the SBP concept are presented with a special focus being laid on studies of island-based SBP systems and the general modelling approaches for the design of SBP systems. Finally, the contributions of each publication to the state of art are summarized at the end of Chapter 3.
4. In Chapter 4, the various studies on SBP systems published during the PhD project are described. For each study, the layout of the studied polygeneration system and a short presentation of the methodological approach used for the techno-economic analysis of the given system are presented. Chapter 4.1 starts with a techno-economic analysis of a biomass-based CCHP system for a hotel complex on the Andaman Islands comparing it to a CHP and two separate production systems. In Chapter 4.2, a biogas-based SBP system for a rural community in Bolivia is described, where two different storage technologies allow for higher flexibility and efficiency. Finally, a response to the question on how small-scale CCHP systems can compete or collaborate with HP is given by two studies presented in Chapters 4.3 and 4.4. The first study of this sub-chapter puts a focus on the techno-economic performance of a combined CCHP/HP system for various climate scenarios, while the second study investigates the exergetic performance of such a system.
5. In Chapter 5, the findings of the studies are then synthesized critically discussed to obtain a coherent picture of the relevance of this thesis for the field.
6. Finally in Chapter 6, the findings of the thesis are summarized and conclusions are drawn. An outlook for future studies and future developments of SBP is given.

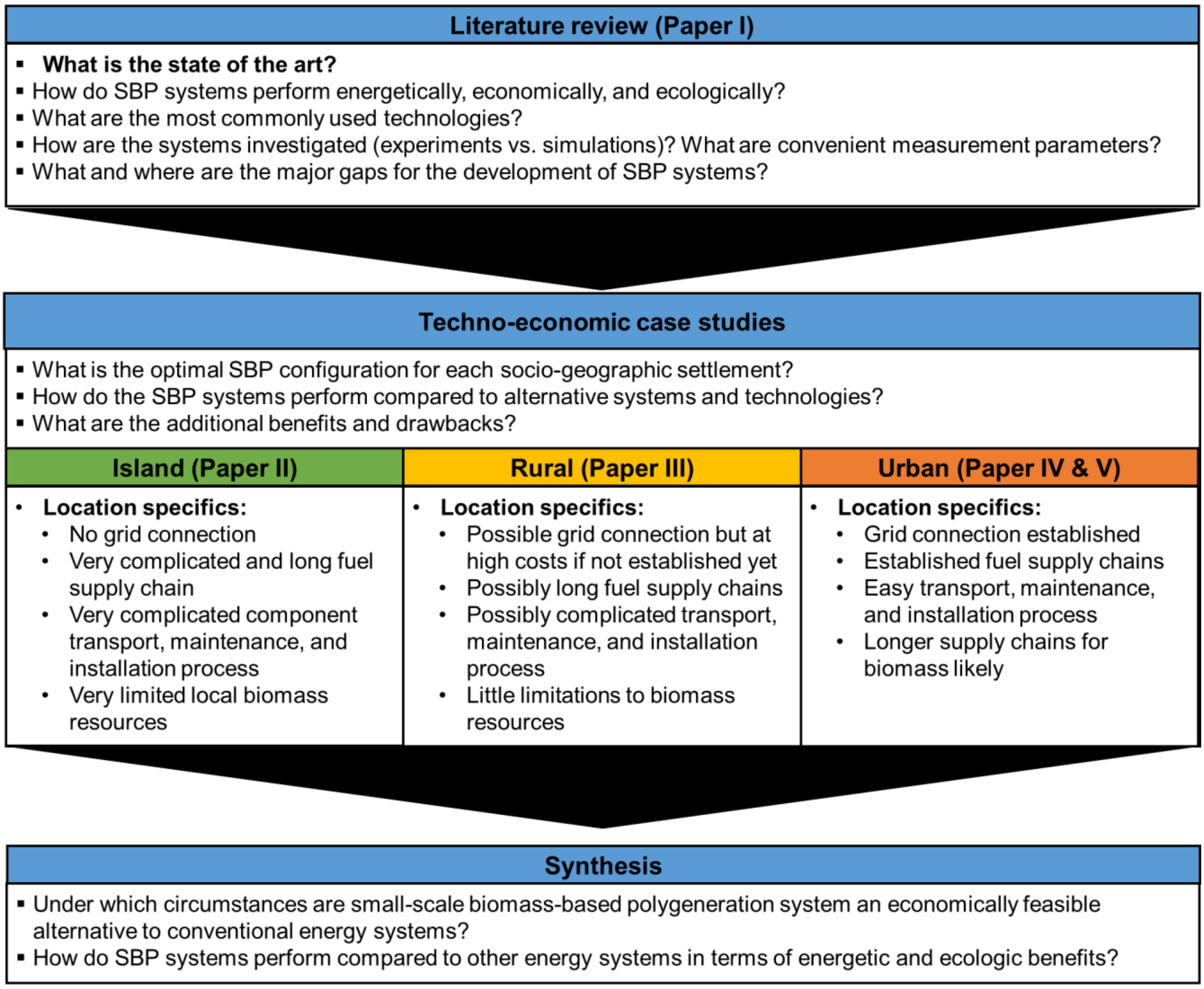
2. Methodology

In this chapter, the overlying methodology for the development of the entire thesis as well as the applied software tools are presented. Additionally, a general methodologic framework used in all modelling studies is presented, albeit it should be noted that the specific methodologies used in each study differ from each other.

2.1. Thesis methodology

To answer the questions raised in Chapter 1.1, a methodological framework has been developed, which is shown in Figure 4. The thesis can be separated in three interconnected work packages:

1. **Literature study:** The thesis is based upon a thorough review of available scientific, technical, and commercial literature. For this, various search tools have been used including amongst others: digital websites, digital and physical literature works stored in university libraries, and digital reference management software. All published papers contain a literature review corresponding to their specific topic, but Paper I surpasses the other papers by presenting a much larger breadth of literature and by analysing the general patterns within the field. However, Paper I is limited to small-scale, biomass-based combined cooling, heating, and power (CCHP) systems and does not incorporate alternative polygeneration technologies. Furthermore, Paper I has been published during the mid-phase of the PhD study, but the processes of scanning, summarising, and structuring literature have never been halted. Therefore, an updated literature review on SBP systems is presented in Chapter 2.
2. **Techno-economic models and case studies:** In this work package of the PhD project, various techno-economic studies on different polygeneration systems in different social and geographical areas were conducted. In each study, polygeneration systems were designed with the aim to optimally fulfil the demands of selected localities given the respective limitations of the local environments. To this purpose, different design and optimization strategies were employed and are presented in Papers II-IV.
3. **Synthesis:** By analysing and synthesizing not only the individual results but also the compound of the studies of the previous two work packages, the general research questions of Chapter 1.1 are answered. As the thesis incorporates this synthesis, it corresponds directly to these questions.



Literature review (Paper I)

- **What is the state of the art?**
- How do SBP systems perform energetically, economically, and ecologically?
- What are the most commonly used technologies?
- How are the systems investigated (experiments vs. simulations)? What are convenient measurement parameters?
- What and where are the major gaps for the development of SBP systems?

Techno-economic case studies

- What is the optimal SBP configuration for each socio-geographic settlement?
- How do the SBP systems perform compared to alternative systems and technologies?
- What are the additional benefits and drawbacks?

Island (Paper II)

- **Location specifics:**
  - No grid connection
  - Very complicated and long fuel supply chain
  - Very complicated component transport, maintenance, and installation process
  - Very limited local biomass resources

Rural (Paper III)

- **Location specifics:**
  - Possible grid connection but at high costs if not established yet
  - Possibly long fuel supply chains
  - Possibly complicated transport, maintenance, and installation process
  - Little limitations to biomass resources

Urban (Paper IV & V)

- **Location specifics:**
  - Grid connection established
  - Established fuel supply chains
  - Easy transport, maintenance, and installation process
  - Longer supply chains for biomass likely

Synthesis

- Under which circumstances are small-scale biomass-based polygeneration system an economically feasible alternative to conventional energy systems?
- How do SBP systems perform compared to other energy systems in terms of energetic and ecologic benefits?

Figure 4 Methodological framework of this study

This study is based fully on computational work ranging from system design over model simulation to optimization algorithms. Nonetheless, in all studies the demand analyses are based on measured real life demand data, while the crucial components of each model are based on technical and scientific data. Three mentionable software tools have been used for simulating the polygeneration systems:

1. **Hybrid Optimization of Multiple Energy Resources (HOMER)** [40]: HOMER has been developed by the National Renewable Energy Laboratory (NREL) in the United States as a software tool to facilitate micro- to small-scale energy system design. After simulating the system performance of one predetermined system design with variable component sizes, HOMER ranks each system according to its best economic performance over the project lifetime. Compared to other software tools used in the PhD studies, HOMER excels in ease-of-use but lacks the possibilities of in-depth component design and control. HOMER has been used for Paper II and Paper III and its operating logic is explained there in further detail.
2. **TRNSYS** [41]: TRNSYS is an open-architecture modelling software for high complexity, transient energy system simulation developed by the University of Wisconsin. TRNSYS comes with a vast set of pre-built components, which have been programmed with the FORTRAN programming language. Compared to HOMER, TRNSYS allows for much more complex system design including more physical and

chemical phenomena. However, TRNSYS is not an optimization software and hence does not find the optimal economic solution of a system design. TRNSYS has been used in Paper IV & Paper V.

3. **MatLab** [42]: MATLAB has been developed by the MathWorks company and is currently one of the most popular programming languages in the field of engineering. While it is a very versatile programming language, it is especially useful for numerical problems and their visualizations. MATLAB has been used in combination with HOMER to allow, amongst others, for a more complex system control strategy in Paper III. Furthermore, a MATLAB environment has been created to allow for economic optimization of highly complex energy systems modelled with TRNSYS, in Paper IV and Paper V.

As HOMER has been developed specifically for the design of energy systems, the calculation processes of the components and their interactions have been validated by various other system modellers. However, in TRNSYS a range of components can be connected in more diverse ways, which can result in incorrect or illogical connections. MATLAB as a programming language, allows for even more freedom in developing the model based on particular software, which only elevates the risk of programming illogical or simply erroneous component behaviour and relationships. Therefore, different validation procedures have been used in order to test the developed TRSNYS and MATLAB models. These validation procedures are:

- Firstly, boundary value analysis with extreme values has been used, where the model is fed with extreme input values and its outputs are scrutinized. In case the expected model output differs from the output calculated by the model, the model has to be revised for possible errors [43].
- Secondly, in a cross-validation analysis the developed models have been fed with input data from other studies and the outputs of the model have been compared with those of the previous studies. In some case, the models have then been extended with sub-models of various new components to allow its application for new polygeneration systems.
- Thirdly, sensitivity analyses have been conducted, where the impact of key input variables on the entire system performance are analysed.
- Fourthly, a white-box testing approach has been chosen for all models, where each component is tested with various input values but also by considering the internal logic of the component model [43].

2.2.General methodology of the modelling studies

For all modelling studies, the primary optimization objective of the developed models is to reduce the project lifetime costs of the proposed SBP system. In all studies, the project lifetime costs are expressed with the variable net present cost (NPC), which is calculated as follows:

$$\mathrm{NPC} = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} = \sum_{t=0}^{n} \sum_{j=1}^{j} \frac{CC_j + RC_j + OM_j + FC_j - SR_j - ES_j}{(1+i)^t} \qquad (1)$$

where R_t are the cashflows for year t, i is the real discount rate and n represents the project lifetime. For each component j, R_t is composed of all capital costs CC_j, replacement costs RC_j, costs and revenues for operation & maintenance OM_j, fuel costs FC_j, salvage revenues SR_j, and energy service sales ES_j. The energy service sales can be any additional service generated by the system that is not supplied directly to the client but sold to external sources. Examples for energy service sales would be excess electricity, excess potable water, and excess biogas. The mathematical formulation of the optimization can hence be expressed as:

$$\min(\mathrm{NPC}), E_{cs} \leq E_{cs,max} \tag{2}$$

where E_{cs} is the annual capacity shortage of the system size iteration and $E_{cs,max}$ is the maximum allowed annual capacity shortage for the system to be considered viable.

The general methodological approach for the design and evaluation of the models developed for the proposed polygeneration system is shown in Figure 5. The modelling approach can be divided into three subsequent sub-processes:

- A demand analysis phase, where the electric and thermal demand behaviour of the end client are determined and analysed based on technical, site-specific, and economic data.
- The model creation phase is initiated starting with the SBP system design, where technologies suitable to satisfy the energy service demands are selected and their layout is determined. For the designed system, a model is devised and validated by comparing it to other models and/or by conducting various input/output tests. The model is then executed for the chosen case study settings and for all considered iterations using a brute-force search approach [39]. For each iteration, the technical outputs are stored and an economic model calculates the corresponding economic performances.
- In the final result analysis phase, the data is structured and visualized in order to facilitate the discussion and conclusions drawn from the results.

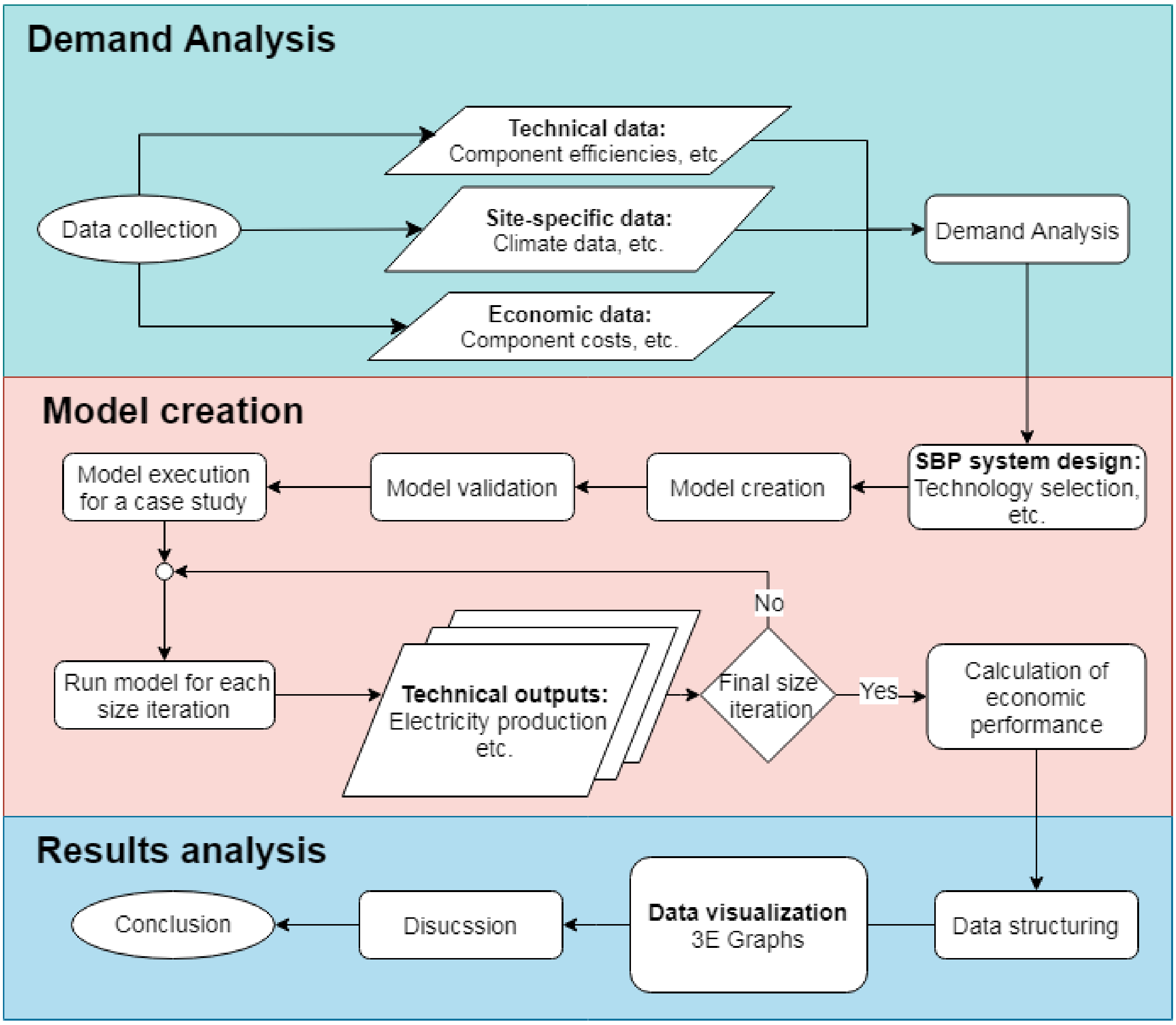


Figure 5 General modelling approach for the evaluation of proposed SBP systems

In some studies the proposed SBP system has also been compared with the reference system using the Levelized Cost of Energy (LCOE), calculated as follows:

$$\mathrm{LCOE} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{E_{served}}} \tag{3}$$

where $\mathrm{C_{ann,tot}}$ are the annualized cost of the system [in USD/yr] and $\mathrm{E_{served}}$ is the total electrical load served for one year [in kWh/yr]. To calculate $C_{ann,tot}$ the following formula is used:

$$\mathrm{C_{ann,tot}} = \frac{\mathrm{i} \times (1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}} - 1} \times \mathrm{NPC} \tag{4}$$

where i, n, and NPC are defined the same as for equation (1). However, one major drawback of the LCOE parameter is that it does not take into account services, which are difficult to express with common energy parameters. For example, it is difficult and may be misleading to include the production of potable water into calculations using LCOE values.

3. Context and state of the art

The major benefits of SBP systems have been listed in Chapter 1. These benefits have made SBP systems an interesting subject for engineers as well as scientists. Hence, in combination with the versatile nature of SBP systems, a multitude of studies on the state of the art of the subject is available. In this chapter a review on the state of the art is presented with a focus on a selected range of technologies and their applications based on the scope defined in Chapter 1.2. Firstly, a general overview on the use of biomass for electricity generation and on distributed energy systems is given in order to locate the thesis within the greater context of the 21st century energy transition. Secondly, a comprehensive review of literature on SBP systems is presented and commonly chosen modelling approaches for SBP systems are outlined. This review summarizes literature on all types of polygeneration systems, but island-based SBP systems and/or SBP systems operating in island-mode will be highlighted. At the end of this chapter, the contributions of each paper to the state of the art are presented in a summarized form.

It should be noted that Paper I already represents a thorough literature review on small-scale, biomass-based CCHP systems. Thus, studies that have been summarized in detail in Paper I are not mentioned in such detail in this review unless it supports the greater argument of the thesis.

3.1. The context of biomass and distributed energy systems

In order to satisfy the world's rising demand for energy while simultaneously to reduce the emissions of GHG, the conception and deployment of more efficient and less polluting energy systems are necessary [44]. While state-of-the-art centralized gas-fired power plants can generate electricity with high efficiencies of up to 61%, the average electric efficiency of thermal power plants employed worldwide is only 41% for gas and 34% for coal [45]. In most cases none of the exhaust heat is recovered but instead given off to the environment, already during the electricity generation phase in the power plant high losses occur. Additionally, due to long transmissions and distribution grids further losses occur until the electricity reaches the final end consumer. For the global average, electricity transport contributes up to 12% of the total electricity losses, but makes up up to 30% of the costs of the delivered electricity [45,46].

By harnessing locally available energy resources to supply energy services in close proximity to the final user, distributed and decentralized energy systems aim to avoid these losses. A list of advantages and disadvantages of decentralized energy systems is shown in Table 2. Arguably, the advantages outweigh the disadvantages, but high obstacles like the increased complexity not just of engineering but also of financing distributed energy systems hamper the installation of such systems.

Table 2 Advantages and disadvantages of distributed energy systems vs. centralized systems

Advantages	Disadvantages
• Much lower electricity transmission losses [30] • Reduced costs for transmission infrastructure due to lower installation, operation, and maintenance requirements [53] • Locally placed CHP means heat can be used directly without any need for heat transmission infrastructure, which in turn raises efficiencies [53] • The quick start-up capabilities of smaller systems increase grid resilience and flexibility [53] • Modular financial structures allow for lower capital costs for individual stakeholders [53] • Higher suitability towards locally available RES [54] • Lower GHG emissions due to higher efficiencies and application of more RES [30,53]	• More control equipment necessary as each plant requires its own control [53] • Higher complexity and more difficulty to synchronize with larger grid systems [53] • Higher risk of local hazard (especially worrisome for urban areas) [53] • Usually, lower system electric efficiencies despite of the higher system energy efficiencies [38]

As indicated in Table 2, distributed energy systems can be used with various RES, of which each source has its individual benefits and drawbacks. Although wind and solar technologies are booming worldwide [47], their weather- and climate-dependent nature impedes considering them as an universal solution [48]. Other RES like hydro or geothermal may serve loads with greater continuity and controllability, but are limited to specific geographic locations [32,33]. Thus, when aiming for providing not just electricity but also other energy services using small-scale CHP or other polygeneration systems, biomass seems to be the most promising energy source for several reasons [49]: biomass-based systems can be installed and operated with considerable flexibility [50], biomass can be obtained as a waste product at low and stable costs [51], and biomass can be stored in solid, gaseous, and liquid form [52].

When considering the final energy consumption, biomass-based solutions still represent the major energy source in the EU as shown in Figure 6. However, most of this biomass consumption is destined for heating either directly at the end client’s structure or indirectly via district heating grids. Only 13.4% of the consumed biomass are used for electricity production and only 12% are used for biofuel generation pointing towards an immense upgrading potential for polygeneration systems of any kind. Within the EU, bioelectricity has experienced astonishing growth rates of 160% over the period from 2005 to 2016 [53] and bioenergy as part of a larger bio-economy is projected to play a key role in the future energy transition [54].

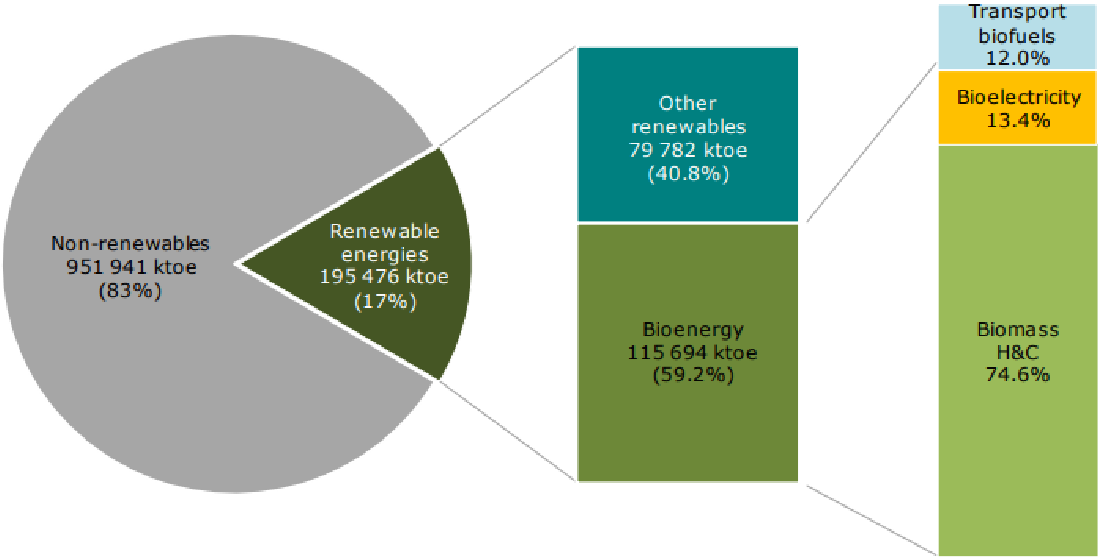


Figure 6 Share of renewables in the EU's gross final energy consumption and biomass contribution in 2016 [53][1]

There are several different types of biomass that can be used for electricity generation as shown in Figure 7 and their individual origin may differ for rural and urban environments as shown in Table 3. The most common type of biomass used for electricity generation are solid biofuels, which in most cases are combusted as either wood chips or pellets. However, biogas derived from agricultural residues, manure, or organic wastes of households has experienced rapid growth in recent decades. Similarly, improvements in management of urban infrastructures have led to a steady rise in electricity generation based on municipal waste. The development of municipal solid waste management will be crucial for achieving sustainability targets of both developing and developed countries. Considering that more countries are also implementing better forest and agricultural management strategies, it can be concluded that the provision of biomass for electricity generation will continue to grow [55].

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[1] ktoe = kilotonnes of oil equivalent with 1 ktoe = 11.63 GWh, H&C = Heating & Cooling sector

Table 3 Rural and urban biomass feedstock sources [56,57]

Rural	Urban
Forest residues and wood waste.	Urban wood waste (packing crates, pallets, etc.)
Agricultural residues (corn stover, wheat stalk, etc.)	Wastewater and sewage biogas
Energy crops (grasses or trees)	Landfill gas
Biogas from livestock	Municipal solid waste and food processing residues

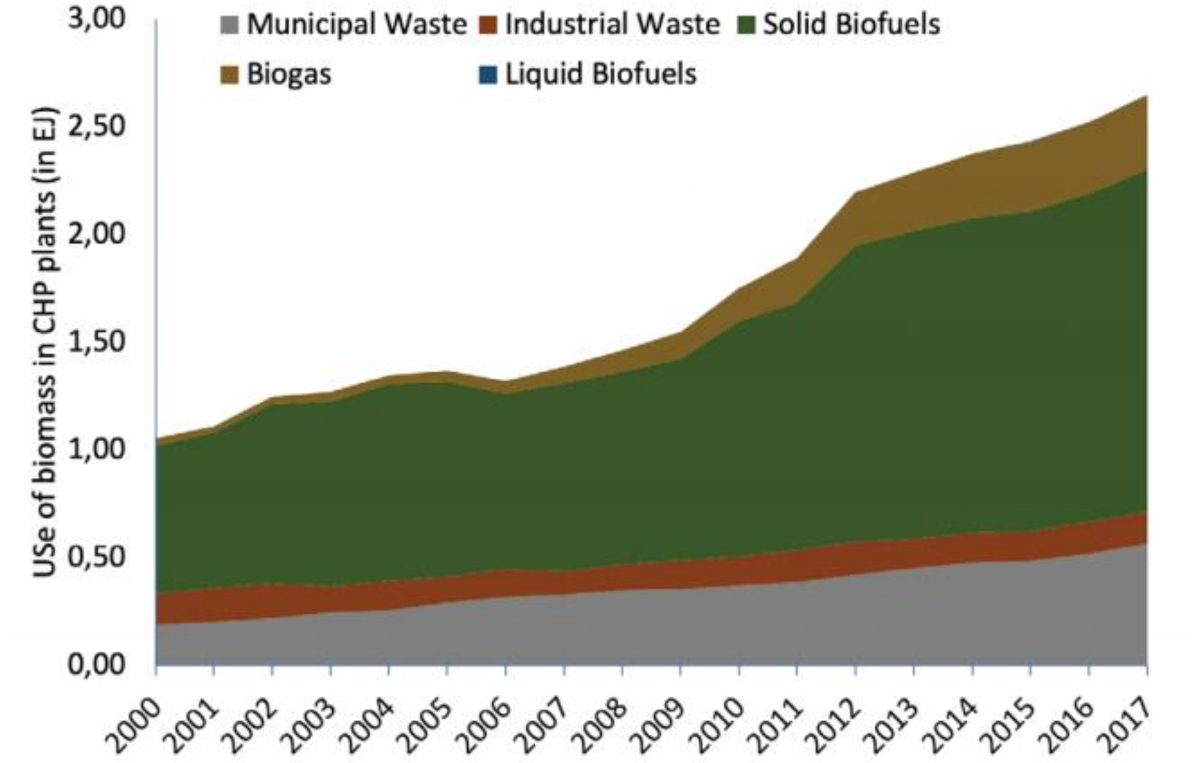


Figure 7 Global electricity generation from different biomass sources [55]

The complex nature of biomass and the many possible conversion technologies complicate any complete analysis of its socio-economic and environmental impacts [58]. However, different types of biofuels can be distinguished according to their origin [59]:

1. First generation biofuels are directly derived from food crops (e.g. rapeseed). These biofuels are heavily criticised not just by many scientists but also by the public, as many negative impacts on food security and biodiversity paired with questionable benefits for GHG emission reductions have been reported [60].
2. Second generation biofuels are based on residues from agriculture and silviculture. They are sometimes considered as a sustainable response to the criticism of first generation biofuels [60] and have experienced considerable growth since the start of the 21st century,
3. Third generation biofuels are based on algae. Such biofuels are still in the development phase with no constructed large-scale facilities existing [61].

Currently, second generation bio-fuels seem to be the favourite choice for CHP purposes in the bioenergy sector [58]. Nevertheless, even when harvested following sustainable criteria, second generation biomass requires management of considerable land area and hence inevitably involves an infringement of humanity into nature. Two advanced conversion routes can be chosen for small-scale second generation biomass conversion:

1. The thermo-chemical conversion route, where thermal energy is supplied to biomass in a low oxygen environment. The thermo-chemical conversion route can be separated into the following processes:
    a. Firstly, in a drying phase the heating value of the biomass is increased by simply removing humidity.
    b. Secondly, in the pyrolysis phase larger biomass molecules are cracked down to smaller ones with the main product being a mixture of various liquid chemical compounds [62].
    c. Thirdly, in the gasification phase the molecules are further broken down with the main product being a mixture of various gases called synthesis gas or syngas [63]. Typical gas composition values for small-scale downdraft gasifiers are shown in Table 4.
2. The bio-chemical conversion route, where micro-organisms break down biomass into smaller molecules. The bio-chemical conversion route can also be separated into different categories:
    a. Fermentation, where biomass crops are first converted to sugars and then fermented to alcohols. This process is used in various countries in large-scale facilities [64].
    b. Anaerobic digestion, where bacteria convert biomass into biogas, which results in a mixture of approximately 60% methane and 40% carbon dioxide [65].

The two most commonly chosen small-scale conversion technologies for second generation biofuels are gasification for woody biomass and anaerobic digestion for agricultural residues [19].

Table 4 Typical syngas composition from commercial wood for downdraft gasifiers [66]

Composition	x_{CO}	x_{CO2}	x_{H2}	x_{CH4}	x_{N2}	Syngas LHV [MJ/Nm]
[% vol]	17-22	9-15	12-20	2-3	50-54	5.0-5.9

3.2. SBP systems

The aforementioned characteristics of second generation biomass fuels fulfil fittingly the requirements of sustainable and decentralized systems [67]. Therefore, various studies have been conducted on a variety of diverse small-scale energy systems based on biomass.

3.2.1. Presentation of selected SBP technologies

Based on the scope of this thesis as described in Chapter 1.2 an overview of the most commonly applied SBP technologies technologies is shown in Figure 8. A detailed description of the here presented technologies is given in Paper I [19].

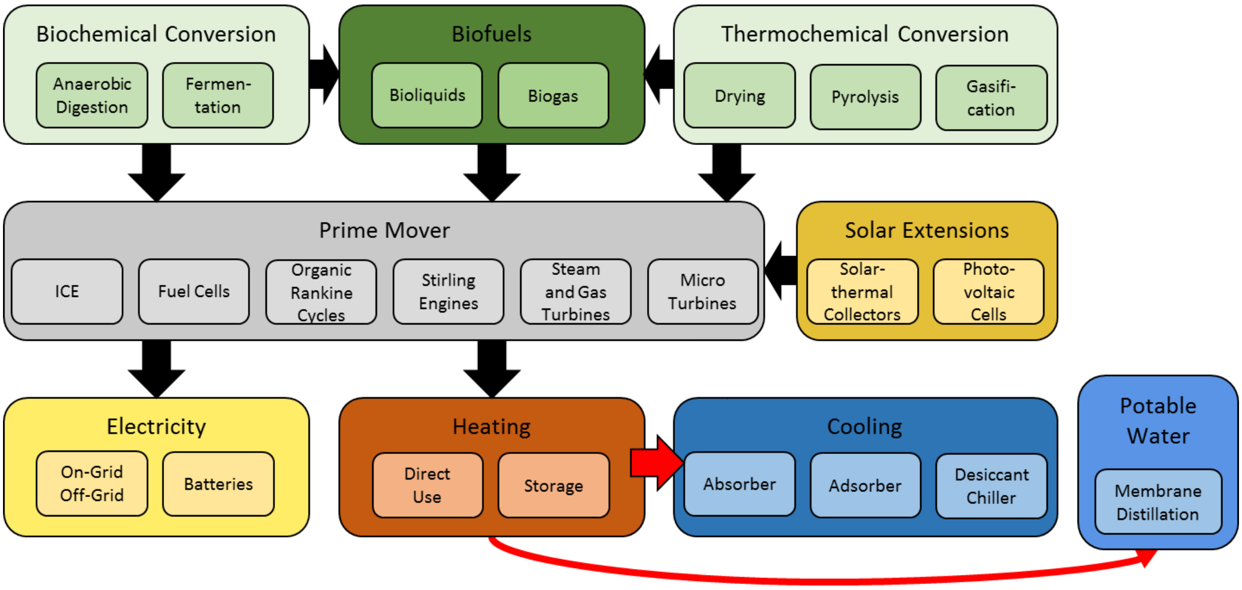


Figure 8 SBP system technologies (based on [19]*)*

The definition of polygeneration varies within the scientific literature and several synonyms have been used in other studies. In the following list, some of these synonyms are defined for this study [19,68]:"

I. Trigeneration: essentially equivalent to CCHP [68]
II. Polygeneration/Multigeneration: Any system which produces more than two energy services; this can be a CCHP system but may also be a system producing chemicals or other products [68,69]
III. MCCHP/ µCCHP: Micro CCHP (with less than 20 kW electric power) [18,31,70]
IV. CHP with Cooling or Cogeneration with Cooling: Essentially the same as a CCHP system [71]
V. BCHP: Building Cooling Heating and Power [72]
VI. Biorefinery – Any system, which produces chemical products out of biomass [68]"

The prime mover is often regarded as the "heart of the polygeneration system" [28,31], because the selection of all other system components directly depends on the prime mover characteristics, which will consequentially determine the entire system economics. Therefore any SBP system is defined by the chosen type of prime mover, the prime mover size, and its operation strategy. As shown in Table 2, each prime mover technology has its individual benefits and drawbacks.

Table 5 Assessment of Prime Movers for small-scale biomass-fired CCHP systems [19]

Prime Mover	***Internal Combustion Engines***	***Fuel Cells***	***Stirling Engines***	***Organic Rankine Cycles***	***Micro Turbines***
Size	*Up to 100 MW* [73]	*Up to 2 MW* [73]	*Up to 150 kW* [74	*Up to 2 MW* [74]	*Up to 1 MW* [31]
Advantages	*Very high reliability (with clean fuels)* [28,31] *Rapid start-up* [31] *Low investment costs* [31]	*Excellent partial load performance* [73] *Very high electric efficiency* [15,31] *Low noise* [28] *Low emissions* [15,31]	*Can use low quality fuels due to external combustion* [31,73,75] *Good partial load performance* [73,75,76] *Potentially low maintenance requirements/ less moving parts* [31,77] *High thermal efficiency* [15] *Low emissions* [15,75]	*Can run with low grade heat* [76] *High reliability* [76,78] *Low maintenance costs* [15,79] *Good partial load behaviour* [78]	*Low quality fuels can be used for externally driven units* [31] *Very few moving parts* [31] *Very compact sizes* [31] *High temperature exhaust* [28] *Low emissions* [28]
Disadvantages	*Short maintenance intervals* [28,31] *Instability with bio- and syngas/ limited fuel flexibility* [31,79,80] *High noise* [28] *High NOx-emissions* [15,31] *Using waste heat difficult* [28]	*Very high investment costs* [15] *SOFCs have long start-up times* [73] *Requires very high quality, energy intensive fuels* [31] *Low heat recovery* [15]	*Still high investment costs* [31] *Low electric efficiency* [15,75] *Technology not fully developed* [28,75] *Difficult to control power output* [75]	*Still high investment costs* [15] *Low maximal electric efficiency* [15] *Low heat recovery for low-grade heat applications* [74]	*Still high investment costs* [31] *Difficult Start-up* [15,31] *Delicate mechanical design* [32] *Low electric efficiency* [81]
Commonness in reviewed cases [19]	*Most common 18/39*	*Rare 3/39*	*Rare 2/39*	*Common 12/39*	*Rare 4/39**
Assessment of potential	*Remains stable*	*High* [28]	*Very High* [74]	*High* [74]	*Very high* [31,82]

*Including Steam & Gas turbines

A visual summary of a meta-data analysis of 41 small-scale, biomass-fired CCHP systems is shown in Figure 4. Internal Combustion Engines (ICE) seem to be the most popular choice for

SBP systems [83], which can be explained by their advanced technology maturity resulting in high reliability and availability. However, high quality requirements have to be met by the fuel inserted into the engine, which in combination with biomass-derived fuels can sometimes cause project complications and/or augmented costs. For small-scale system applications ICE engine electrical efficiencies can reach up 35% [84], but in combination with biomass lower electrical efficiencies should be expected. Studies on the application of ICE for SBP systems range from engines with electric capacities of a few kW [85,86] to several hundreds of kW [72,87].

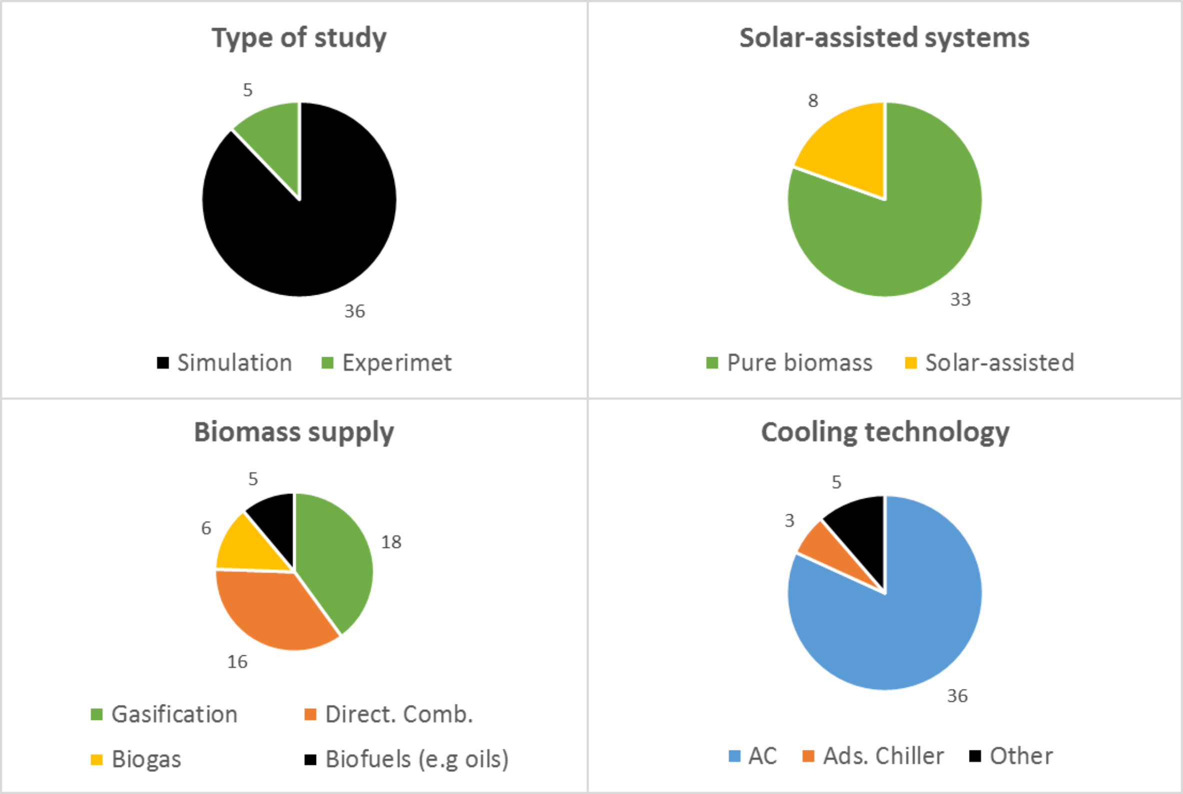


Figure 9 Meta-data results of the 41 different systems studied (multiple component application possible) [19]

The commercially most successful competitor to ICE technologies are systems based on organic Rankine cycles (ORC), where an organic fluid allows operation of a steam-driven expansion cycle at temperatures lower than required for water-based systems. This suitability for low grade heat applications is especially desirable with biomass-based systems [76] and hence many studies on ORC-based SBP systems have been presented. Interestingly, ORC show great adaptability towards other prime movers as shown in studies where a micro-turbine has been used as expanding device [88] or where the ORC has been installed after a fuel cell (FC) system [89]. Other technologies like FC and Stirling engines show great future potential for the use in SBP systems, but their relatively low reliability and stability with biomass-based fuels currently hinder their wide-spread commercialization.

Apart from directly using the recovered heat from the prime mover for heating purposes, transforming the thermal energy into cooling energy is a commonly chosen choice, especially for raising energy efficiency in building systems in warmer regions. Three technologies for thermally-driven cooling have been commercialized and are occupying different parts of the thermal-cooling market [90]:

- Absorption chilling
- Adsorption chilling
- Desiccant chilling

The most common thermally-driven cooling technology is absorption chilling, where the heat recovered from the prime mover is used to separate a working fluid from an absorption mixture through evaporation. The working fluid is then cooled down in order to condense and eventually led to an evaporator, where it absorbs heat at low pressure and hence cools down its surroundings. Eventually, the working fluid is led back to the absorption mixture and is reabsorbed. A simplified working scheme for an absorption refrigeration cycle is shown in Figure 10.

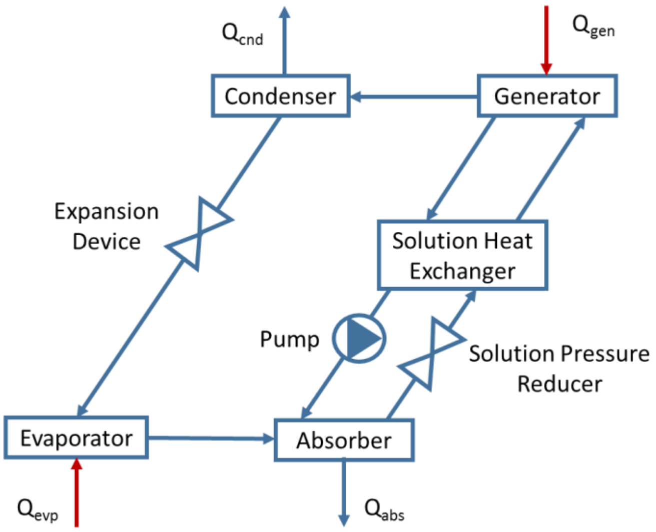
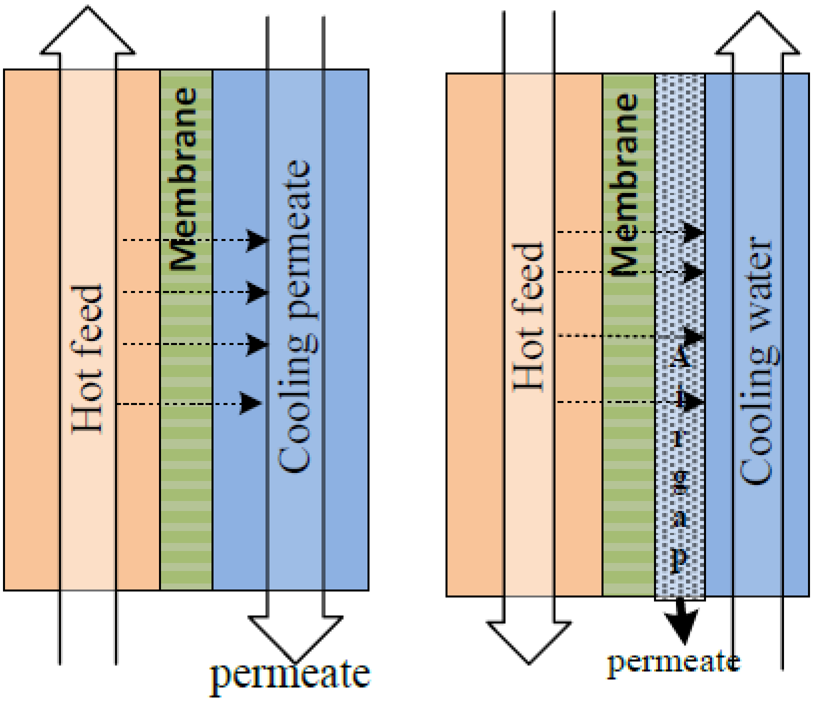


Figure 10 Simplified process of an absorption refrigeration cycle (based on [91]*)*

The recovered thermal exhaust heat from the prime mover could also be used for generating potable water by using thermally-driven water purification technologies. For low-temperature heat applications various types of membrane distillation (MD) technologies seem to be the favourable option compared to pressure-driven technologies like reverse osmosis (RO), which are more common for general applications. In a MD process vapour from a hot feed water loop passes through a porous, hydrophobic membrane and is then condensed by a cooled down receiver plate. Two exemplary configurations of MD unit configurations are shown in Figure 11. The advantages of MD compared to competing technologies are lower energy costs, lower operating temperatures, and lower space requirements [92].



a) DCMD b) AGMD

Figure 11 Two exemplary MD configurations: Direct Contact MD and Air Gap MD [92]

In combination with solar energy, several design strategies can be chosen for SBP systems:

- solar-thermal energy can be used for pre-heating biomass for the biomass conversion process [93,94]
- solar thermal energy can also be used for pre-heating steam before turbine entry, especially in combination with ORC and/or micro turbines [95]
- solar-thermal energy can be used to raise waste stream energy levels after fuel combustion [96,97]
- PV panels can support the prime mover in meeting the electricity demands [98]
- Batteries, PV panels, and solar thermal collectors can be used to substitute the prime mover entirely, so that the biomass is used only for supporting in generating thermal but not electric energy [99].

3.2.2. SBP systems cooperating with other technology concepts

The EU has identified the use of woody biomass for district heating as crucial for the energy transition and Nordic countries have been pioneering the construction of such systems [100]. Therefore, some scientists study how SBP systems can be best integrated not just intro the electric grid but also into district heating networks. Paredes-Sánchez [101] present a detailed ORC-based micro-cogeneration system, which can be operated with several fuels including local biomass, and analyse how various such systems interlinked in a nodal network could provide thermal and electrical energy for a mining area in Northern Spain. They conclude that the proposed system network would be economically viable and bring important economic, social, and environmental benefits to the region. Arnaudo et al. [102] investigate the potential of locally placed HP in combination with biomass-based CHP plants and thermal storage strategies for a greater thermal network. When employing the locally sourced HP, significant cost and emissions reductions can be obtained. This shows that the cooperation of SBP systems and HP can lead to improved total system performance.

Some studies have also been conducted for the end-user level on the combination of polygeneration systems and HPs. Mancarella [103] presents a general modelling approach on how to optimally size components of a CHP/HP system by identifying key parameters for the decision makers. He shows that the CHP/HP sizing but also the expected emission and fuel reduction rely heavily on the heat-electricity demand ratio of the end client. A graphical calculation tool for combining CHP and HP systems based on off-design operation conditions is proposed by Lo Basso et al. [104], who highlight that the economic viability depends heavily on the electricity price. Specifically for the coupling of CCHP systems with a ground-sourced heat pump (GSHP) system, Zeng et al. [25] employed a multi-population genetic algorithm, while Li et al. [105] used a quantum genetic algorithm for a similar system. In both studies the proposed system show energetic and environmental performance improvements compared to separated generation systems.

Even though the previously mentioned studies focus on optimization of combined CHP/HP or CCHP/HP systems, all of them focus on fossil-fuelled systems and hence do not investigate the economic as well as environmental impact of biomass-based fuels on such CCHP/HP systems. A study taking this neglected factor into account could facilitate the design of CCHP/HP systems and further promote the SBP concept.

Although the biomass used in SBP can be considered as a form of energy storage, the SBP concept can be further enhanced with other energy storage technologies to create a Hybrid Energy Storage System (HESS). Just as with polygeneration, the concept of HESS encompasses numerous developed and developing technologies ranging from fast reacting super-capacitors over all sorts of electro-chemical batteries to long-term storage technologies like pumped hydropower plants. Commonly a “sprinter”-“marathon runner” combination is used [106]:

- The “sprinter” device serves primarily short-term load fluctuations, which requires technologies with fast response times and high cycle lifetimes.
- The “marathon runner” serves primarily long-term load demands and hence requires technologies with low self-discharge rates and lower energy specific costs.

By decoupling the requirements for long-term energy storage and short-term power serving, the total investment costs of the storage system can be decreased. Additionally, the storage system efficiency can be increased, as the two technologies can be operated closer to their optimal operation profiles. However, the optimal operation of both technologies will also require sophisticated control strategies and mechanisms. Moreover, the reduction of short-term strains on the “marathon runner” can also lead to increased lifetimes of the long-term storage device [38]. A thorough overview of how storage technologies can be combined has been presented by Bocklisch [38],while a review focusing specifically on HESS for microgrid applications has been given by Hajiaghasi et al. [107]. Both reviews highlight the potential of the HESS concept, especially in combination with RES, and both underline the complexity of designing such HESS. However, neither of the authors considers biomass explicitly in their reviews on HESS, but hydrogen is mentioned as a potentially biomass-derived fuel. There are few studies considering biogas in combination with other storage technologies for RES systems. Rad et al. [108] present various hybrid PV/wind turbine/biogas generator/FC systems for on- and off-grid use in a rural settlement in Iran. They conclude that the most cost-effective solution is a PV/wind turbine/biogas generator combination, while the FC would not improve system economics. Although a detailed analysis on the biogas potential is conducted, no specific details are presented on the biogas storage facilities and subsequent storage strategies.

There are many similar studies considering biomass for hybrid-energy systems (e.g. [109–111]), but none of these studies consider explicitly the storage control strategy of the HESS. Hence there is a gap in the state of the art considering the optimal control strategy of biogas and batteries for SBP systems.

3.2.3. Effects of climate variables on SBP systems

Some of the most recent studies on SBP systems consider not just how technological but also how geographical aspects influence system performance. Depending on the geographical region the energy service demands of the end client will vary greatly. Especially for CCHP systems, more extreme climates seem to be favourable, because these regions demand more cooling as well as heating from the energy service provider. For example, Mouaky et al. [112] investigate how parabolic collectors can support the biomass conversion process for a 46 kW_e ORC-based system located in a semi-arid, rural region of Morocco. After expansion in the ORC turbine, the remaining heat of the working fluid is used for water purification via a RO unit and for heating up domestic hot water (DHW). The system would produce electricity, fresh water, and DHW at relatively high cost compared to market costs. However, the remote location of the studied system may justify such a high price discrepancy. The system performance is also highly influenced by ambient temperatures and solar radiation.

In a study by Sigarchian et al. [113] the effects of various climate zones of Iran on the design and performance of a CCHP system are investigated. Although different climate zones require different sizing of the CCHP components, it could be shown that in all cases the CCHP system shows great environmental and energetic performance. Yet only in the hottest climate the CCHP system would lead to cost reductions, while in the other zones the CCHP systems would be economically unfeasible due to too low cooling demands. In a similar study by Ebrahimi et al. [114] a CCHP system is optimized for 5 different cities in Iran. They found that fuel savings of up to 38% can be achieved depending on the region with high system efficiencies of up to 85%. However, none of these studies consider the foreseeable impact of climate change on the component performance and the system design of SBP systems.

The environmental climate does not just influence the SBP system component design but also the system and component control strategies. Apart from the ambient climate, the load control is influenced by other system components and by the demand characteristics of the end client. In turn, control algorithms can reach significant complexity levels. The most common strategies are:

- Following Electric Load (FEL): The prime mover power output is set to always fulfil the electric energy demand of the end client.
- Following Thermal Load (FTL): The prime mover output is set to always fulfil the thermal energy demand of the end client

However, many researchers propose hybrid control strategies using each of the previous or entirely new control strategies depending on different decision criteria. Sigarchian et al. [115]

developed a modified base load control strategy, where the prime mover is operating according to FEL, but has not to fulfil the electricity demand entirely and can hence be downsized. Comparing the new control strategy to FEL and FTL using a case study for a residential building in the temperate climate of Northern Italy, they conclude that each strategy has its benefits and drawbacks; while the new control strategy requires the least capital costs, FEL allows for the most energy autonomy while FTL shows the best environmental performance. Li et al. [105] compared five different control strategies for a fossil-fuelled CCHP/GSHP system in a hotel in China. They did not identify any significant performance differences between FEL and FTL strategies, but stated that their strategy of following maximum electric efficiency shows the best results for the case study. On the other hand, in their study on the optimization of CCHP/GSHP systems Kang et al. [116] found indications that FTL may be more suitable for extreme weather conditions, while FEL seems to be better for mild climates.

Studying any given system for all climate zones and applying all developed control mechanisms would be an overly exhaustive task. Therefore, suitable software and control mechanisms for a given case study must be chosen carefully and based on scientific findings.

3.2.4. Specific examples of island-based polygeneration systems

The promotion of RES on islands has received increased interest in recent years, which results in initiatives like the Global Renewable Energy Islands Network (GREIN) founded by the International Renewable Energy Agency (IRENA) and supported by the United Nations [117,118]. Several investigation groups and authors investigated the potential for renewable energy systems on specific islands, island archipelagos and/or islands groups. Blechinger et al. [119] provide an overview for nearly 1,800 islands with a population of up to 20 million inhabitants collecting data on economic development, energy demand and respective fuel costs. Their findings reveal that on all the islands in total 15 GW diesel-systems are operating and that a potential for 7.5 GW PV systems and 14 GW wind systems exists, which could be installed and produce electricity not just much more sustainably but even more cost-efficient. Seizing this potential would imply a 50% reduction of fuel consumption and an electricity cost reduction of nearly 0.10 USD/kWh could be accomplished when also considering battery storage measures. Many studies underline also the necessities for energy storage on islands in order to increase the share of RES [120,121].

Considering SBP systems on islands, Karellas et al. [122] presented a micro-scale ORC system with a peak electricity output of 6 kW, which uses a VC chiller of ca. 10 kW cooling capacity. By superheating the working fluid after the reactor with parabolic trough-collectors the efficiency is further increased. Applying the system in a case study for the Greek island of Milos, an payback period of 7 years was estimated for the worst-case scenario. Salehin et al. [123] simulated a solar PV-biogas-diesel hybrid energy system for the island of Adorsho Char, Bangladesh. The system consists of 7.2 kW solar PV panels, a 16 kW biogas generator, a 9 kW Diesel generator and 12 batteries (1,900 Ah each). The simulations show that electricity can be provided to the underdeveloped island with just 0.217 USD/kWh. A very specific and very innovative example of a trigeneration system based on renewable energies has been presented by Calise et al. [124]. They propose to use geothermal energy on the volcanic island of Pantelleria in the Mediterranean Sea and support the system with concentrating photovoltaic-thermal (PVT) collectors. By using multi-effect distillation, the system can produce potable water and by using an absorption chiller (ABS), it can provide cooling energy. After analysing the system performance economically, they conclude that even without government funding, a payback period of less than 10 years will be achieved, but that feed-in tariffs could substantially lower the payback period.

Although all the previously mentioned studies present energy systems for islands based on RES, none of them analyse the technical and socio-economic aspects of a solar-assisted, biomass-based SBP system. As both, solar energy and biomass may be locally available on islands, such a SBP system could lead to significant emissions savings and cost reduction not just for one individual system owner but for the entire island population.

3.2.5. SBP systems modelling

Many approaches to compute energy system models can be followed, which can be separated into two categories: optimization and simulation models [22]. While optimization models try to find the optimal solution of a decision criteria, simulation models try to replicate the physics of a given system as close as possible. However, the lines between the two categories are naturally blurry because each optimization model needs to simulate at least to a minimal degree the physical laws of a given energy system. The techniques used in optimization models can be separated into two categories again:

1. Mathematical programming including linear programming (LP), mixed-integer linear programming (MILP), and mixed-integer non-linear programming (MILNP). Some specific examples for small-scale energy system models are given by Bischi et al. [125] using MILP for optimal sizing of CCHP systems and by Hemmati et al. [126] using MILNP for the optimization of micro-grid RES systems.
2. Metaheuristic algorithms including genetic algorithm (GA), evolutionary algorithm (EA), and particle swarm optimisation (PSO). Some specific examples for small-scale polygeneration system models are given by Zeng et al. [25] using a multi-population GA to optimise a CCHP/GSHP system, by Sigarchian et al. [113] optimizing a CCHP system for various climates using PSO, and by Hajabdollahi et al. [113] using evolutionary algorithms for CCHP plant optimization.

Numerous other examples of how both types of optimization techniques can be used for polygeneration system modelling can be found in the literature. For a wider selection of studies it is here referred to Mavromatidis et al. [22].

For simulation models, it is often more convenient to use established energy engineering software, where individual components have already been programmed and validated by other scientists and/or engineers. Exhaustive reviews have been presented by Sinha et al. [127] and Lyden et al. [128] listing some of the most popular software tools. These are amongst others: TRNSYS [41], HOMER [40], Hybrid2, RETScreen, iHoga, Modelica, and Aspen Plus. For this thesis TRNSYS and HOMER have been used as explained in Chapter 2. Each energy system simulation software has its benefits and drawbacks, which is why the selection of the software has to be carried out prudently. However, most of these tools are merchandised by commercial enterprises, which may limit the choice of the researcher.

3.3. Contributions to the State of the Art

Several gaps within the state of the art have been identified in the literature review of the previous chapters. The compiled publications on which this thesis is based aim to explore these gaps and contribute to the knowledge missing to fill them. A summary of the main contributions of each paper is given in Table 6. It must be mentioned that the identified gaps represent just a few of the many possible questions to be researched in the context of SBP systems. Some further research directions will be stated in the final chapters.

Table 6 Contributions of the appended papers to the state of the art

Paper I	Biomass-fired combined cooling, heating and power for small scale applications – A review
Contributions	• Structured summary of the scientific literature on small-scale biomass-fired CCHP systems • Meta-analysis of case studies on small-scale biomass-fired CCHP systems and the technologies used to investigate such systems
Paper II	3E-Analysis of a Bio-Solar CCHP System for the Andaman Islands, India—A Case Study
Contributions	• 3E-analysis of a solar-assisted SBP system optimized for project lifetime costs in an island setting • Identification of socio-economic benefits of the studied system for primary stakeholders and the whole island community
Paper III	Techno-economic optimization model for polygeneration hybrid energy storage systems using biogas and batteries
Contributions	• Presentation of a novel SBP system design including HES, water purification technology, and PV-battery assistance • Techno-economic optimization model for biogas-battery HES polygeneration systems including a novel dispatch control strategy applications aiming for maximum biomass utilization • 3E-analysis of the proposed system in comparison to a fossil-fuelled reference system for a rural environment
Paper IV & V	A techno-economic optimization model of a biomass-based CCHP/Heat Pump system under evolving climate conditions
Contributions	• Development of an optimization approach for CCHP/HP systems for various climate scenarios • Presentation of a transient optimization model for biomass-based, PV-battery assisted CCHP/HP systems with a special focus on component efficiencies in relationship to ambient temperature changes • 3E and exergy analysis of various CCHP/HP systems in comparison to an only-HP system in an urban environment

4. SBP models and case studies

In this chapter, all publications compiled for this thesis will be briefly summarized and their main findings will be recapitulated. For each paper, the methodology and a description of the case study will be presented in order to explain how the main findings of each publication have been derived. Finally, some concluding remarks on each publication and how they impact the research on SBP will support the synthesis of the research topic.

4.1. Techno-economic optimization of small-scale, biomass-based CCHP system for an island resort structure (Paper II)

In the following study the viability of various energy systems for a small hotel complex on Neil Island, one of the Andaman Islands in the Bay of Bengal, has been analysed using the 3E approach. The aim of the study was to identify the benefits and drawbacks of a small-scale, biomass-based CCHP system with PV-battery assistance in comparison to separate production of a diesel-fuelled reference system as well as to an only PV-assisted diesel system and a PV assisted biomass-based system without polygeneration measures. Crucially, the study focused not just on the techno-economic performance of the proposed energy systems, but also on the greater socio-economic effects on the island and its inhabitants.

4.1.1. Case description and technical input

During the time of the study, the Andaman Islands were heavily dependent on petroleum imports for their energy system with over 90% of the electricity generation having been supplied by diesel generators [129]. In turn long and instable transport chains led to increased energy prices and higher emissions, while especially on Neil Island frequent breakdowns of the electric grid occurred. Therefore, the hotel owner has shown interest in renovating his 40 guest room hotel structure including a more self-sustaining, sustainable, and cost-effective energy service provision system. The hotel is located at approximate latitude 11°59′ and longitude 92°7′ receiving an average daily solar radiation of 4.72 kWh/(m^2·day). Hence, the conditions for PV panels have been considered as very satisfactory.

Based on building characteristics and occupant profiles, the electric demand profile of the reference system has been calculated with the electric load for one entire year as being shown in Figure 12. The thermal demand of the hotel rooms and the service installations have been calculated based on minimum requirements as formulated in the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard [130]. The daily peak electrical demand time starts at 18:00h and ends at 22:00h with no major alteration in the curves for weekdays and weekends. During the high tourist season from November to March the average demand is significantly higher than during the low tourist season from April to October. Because this demand contains electricity for thermal as well as non-thermal services and because the CCHP system provide parts of the thermal services using thermal instead of electric energy, the electricity demand curve for purely electric service appliances will be lower for the CCHP system.

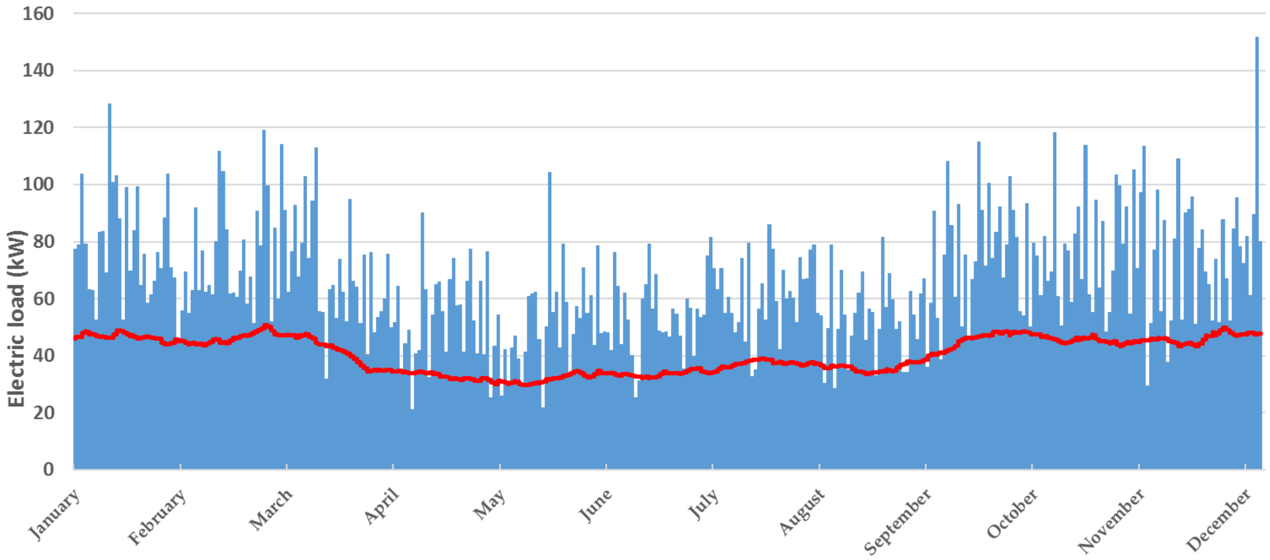


Figure 12 Max. electric load for each hour of the year in blue and 30-day average in red [131]

After the system demand analysis, the following energy system layouts have been taken into consideration for analysis:

- **Reference case 1:** The hotel receives electricity from the grid from 00.00-18.00 and operates a diesel engine from 18.00-24.00, which is when the grid most frequently brakes down.
- **PV-Battery case 2:** As above, but the system is now supported by PV panels and batteries.
- **PV-Battery-Biomass case 3:** As above, but the system uses a biomass downdraft gasifier connected to a gas engine instead of a diesel engine.
- **PV-Battery-Biomass CCHP case 4:** As above, but the system operates now entirely off-grid and the exhaust heat from the gas engine is recovered and used for water heating and for cooling via an ABS. A biomass boiler has been added for thermal energy provision whenever the engine is not running or not providing sufficient heat. The CCHP system layout is shown in Figure 13.

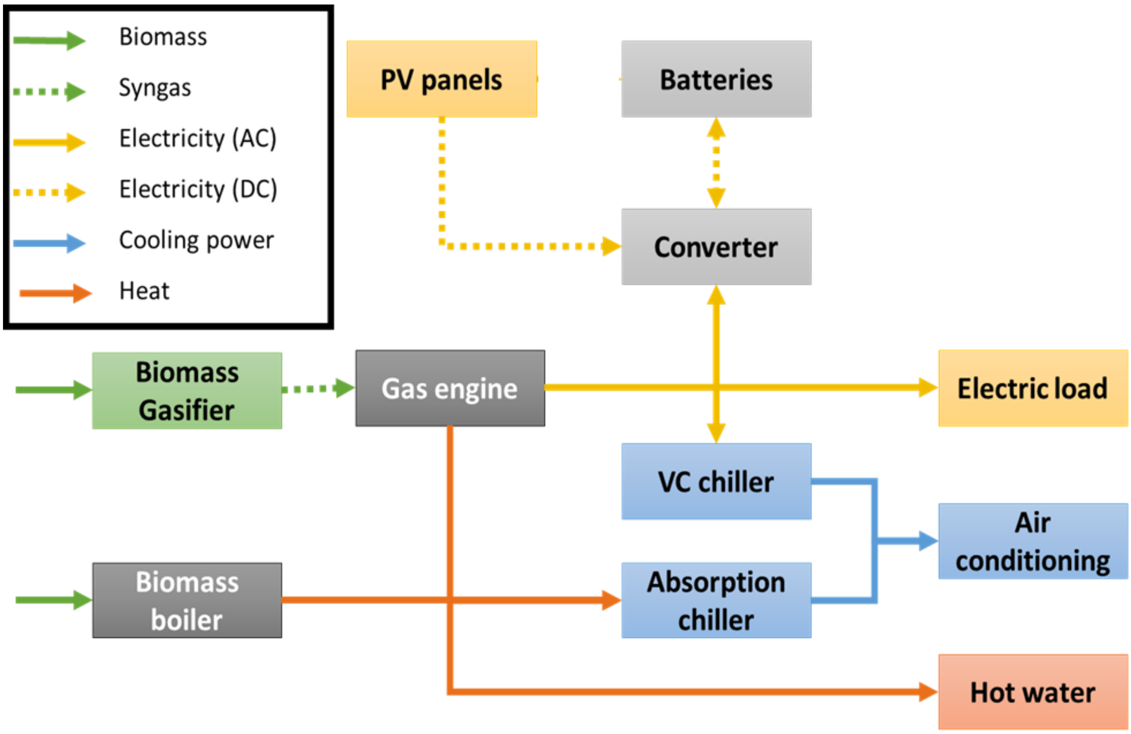


Figure 13 Simplified system sketch of the CCHP system [131]

Several key technical and economic input parameters for the system calculations are shown in Table 7. The data was collected during the time of writing the paper (i.e. 2017). By recovering part of the engine exhaust heat, the electrically driven heating and cooling systems of the hotel are relieved. The formula of electric energy saved $E_{s,h}$ by using part of the engine exhaust heat for domestic water heating is:

$$E_{s,h} = \frac{Q_h}{COP_{elec,h}} \tag{5}$$

where Q_h is the direct heat provided by the CCHP system and $COP_{elec,h}$ is the Coefficient of Performance (COP) of the electrically driven heaters.[2]

Similarly for the thermal-driven cooling provided by the CCHP systems, the electricity savings can be calculated with:

$$E_{s,c} = \frac{Q_c \times COP_{ABS}}{COP_{VC}} \tag{6}$$

---

[2] The generally used equation to calculate the COP is:

$$COP = \frac{Q}{W}$$

where Q is the supplied thermal energy of the HP and W is the used work (most often in form of electricity) supplied to the HP.

where Q_c is the recovered heat used for cooling, COP_{ABS} is the COP of the absorption chiller and COP_{VC} is the COP of the electricity-driven vapour compression chiller (VC).

Table 7 Summary of the component input data [131]

Component	Capital & Replacement cost	O&M cost	Further characteristics
PV panels	1,000 USD/kW & 1,000 USD/kW [132]	25 USD/yr/kW [133]	Lifetime: 25 years Slope: 12° Max. Efficiency: 15%
Batteries	1,500 USD/kW & 1,500 USD/kW [134]	30 USD/yr/ battery [134]	Model: Surrette 4-KS-25PS (1,900Ah, 4V Deep) Cycle Battery [134] Minimum battery lifetime: 7 years Lifetime Throughput: 10,973 kWh
Gasifier + Gas engine	3,000 USD/kW & 3,000 USD/kW	0.03 USD/kWh [85]	Lifetime of both: 15,000 hours [135] Gasifier efficiency: 75% [136] Engine max. efficiency: 24% [137]
CCHP measures	25,850 USD for entire equipment	0.013 USD/kWh [85]	75 kW Heat exchanger 42 kW AC (COP: 0.6) [138] Capital cost (incl. engineering &transport) 20 year lifetime Biomass availability: ,273 MWh/yr [51]
Converter	750 USD/kW & 750 USD/kW [139]	10 USD/yr/kW [133]	Lifetime: 20 years, Inverter efficiency: 90%, Rectifier efficiency 90%
Diesel Engine	600 USD/kW & 600 USD/kW [139]	0.02 USD/kWh [139]	Lifetime: 20,000 hours Minimum partial load: 40% [140] Maximum efficiency: 38% [140] Forced on from 18.00-24.00 every day

4.1.2. Main findings

For each case, the corresponding component sizes have been determined following the optimization procedure with the results being shown in Table 8. In case 2, the installation of electrical energy storage in form of batteries and additional electricity generation support in form of the PV panels allows for a significant downsizing of the diesel generator. Although the PV panels charge the batteries during the day, they do not support the entire energy system during peak demands after 18.00 and hence after sunset. Therefore in case 3, the battery capacity increased in order to fulfil the demands of the maximum capacity shortage constraint in combination with the gas engine. The CCHP measures of case 4 allow for further downsizing of all components compared to case 3.

Table 8 Optimal system configurations for all cases [131]

Component	**Case 1 (Diesel-Grid)**	**Case 2 (Solar-Assisted)**	**Case 3 (Bio-Solar)**	**Case 4 (Bio-Solar CCHP)**
Diesel generator	160 kW	90 kW	-	-
Gasifier + Gas engine	-	-	50 kW	40 kW
PV panels	-	200 kW	85 kW	85 kW
Batteries (Nom. Capacity)	-	42 kW in 7 strings (319 kWh)	84 kW in 14 strings (638 kWh)	48 kW in 8 strings (365 kWh)
Converter	-	60 kW	50 kW	45 kW
Boiler	-	-	-	75 kW

The main economic and environmental findings of the study are summarized in Figure 14. All three of the proposed RES systems are more cost-effective over the project lifetime of 20 years than the reference system, however all of them require higher investment capital too. The higher costs of the reference case system are mainly caused by higher fuel and electricity costs. Notably, the much easier-to-install system of case 2 shows a similarly good economic performance as the complicated system of case 4, albeit it may not lead to full energy autonomy and requires more capital investment. Case 4 would lead to lifetime savings of nearly 30% equivalent to more than 500,000 USD, which could be used as a reasoned argument to convince possible investors. The yearly CO_2 emissions of the biomass-based systems due to operation would be zero as the biomass has been considered carbon neutral assuming it is harvested according to sustainable management measures. However, this excludes emissions due to biomass transport to the system site and any inherent emissions for constructing as well as eventually destructing the required machinery. While the capital investment costs are foreseeable during project design and installation, the fuel costs can vary. The results of the sensitivity analysis have shown that the fuel costs have a larger impact on the systems of cases 1 and 2, meaning that the biomass-based systems are more robust towards fuel price shocks.

The holistic benefits and drawbacks of the proposed CCHP system not just for the hotel owner but also for other island inhabitants are summarized in Figure 15. By implementing long-term biomass supply contracts between local farmers and the hotel owner, the biomass farmers would have an additional and stable income source. The local administration would benefit by reducing the strain on the local electricity grid and increasing the autonomy of their entire energy system. Apart from the aforementioned techno-economic benefits of the CCHP system, the hotel owner could also promote his resort as more eco-friendly.

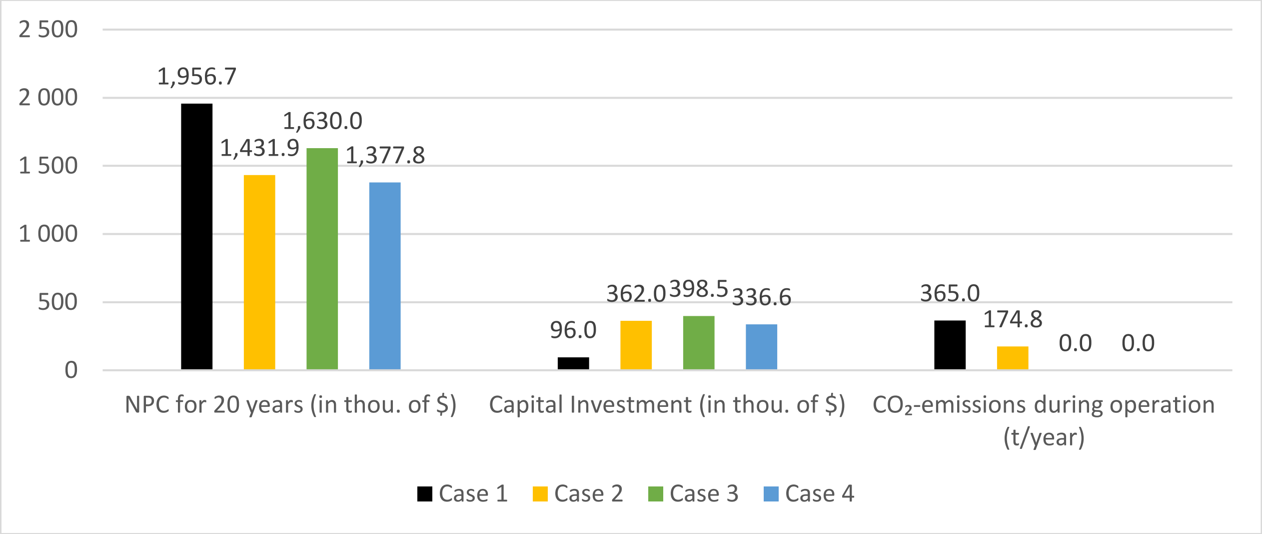


Figure 14 Comparison of NPC, capital investment, and CO_2 emissions for all four cases [131]

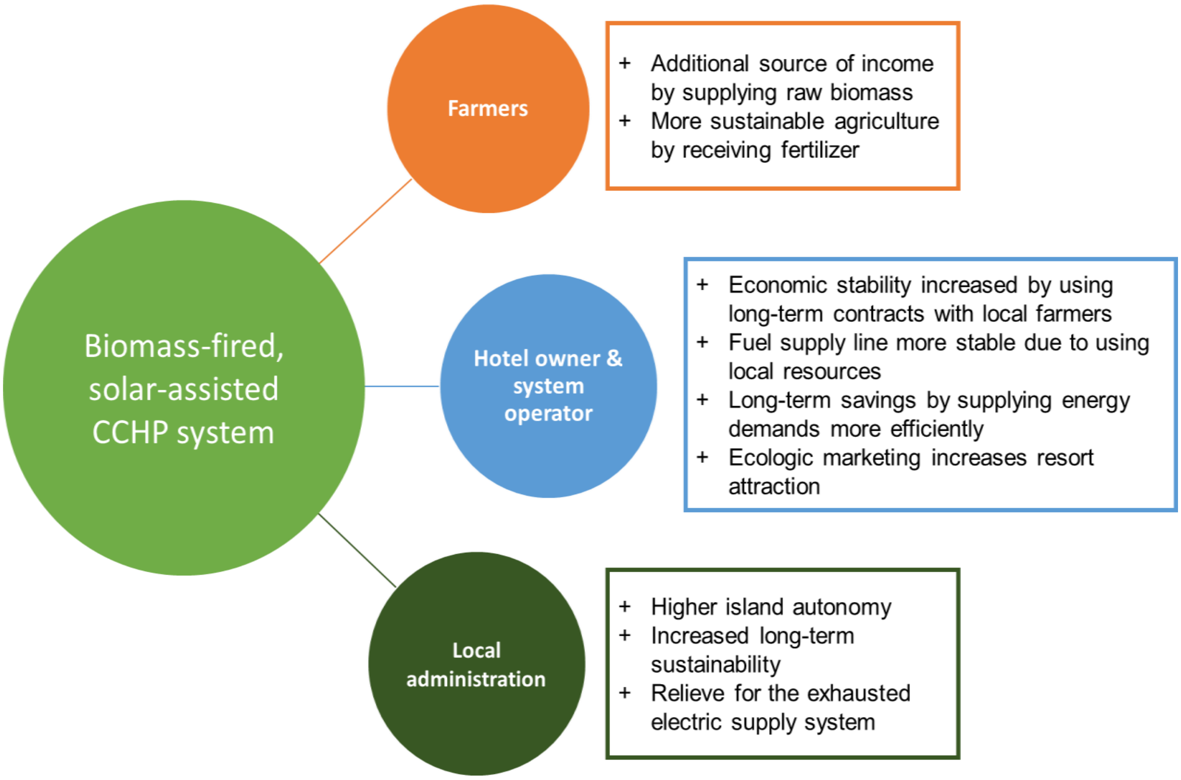


Figure 15 Benefits of a smart CCHP system for various interest groups of the Andaman Islands [131]

4.1.3. Concluding remarks

The study responds directly to the two research questions asked in Chapter 1.1 showing that for islands with insufficiently supplied and deficiently managed fossil-fuelled energy systems, a well-designed SBP system can significantly outperform the reference system economically and environmentally. Additionally, when setting up an intelligent biomass supply structure, not just one singular entity but the entire island society could benefit. However, the potential of biomass especially on smaller islands is much more limited, meaning that the SBP approach can only partly help with the island’s energy transition. Other RES cannot be discarded when aiming for a 100% renewable electricity supply. Additionally, although the SBP system outperforms the reference system in theory, practical obstacles like high design complexity, augmented maintenance and operation requirements, and increased capital investment costs will slow down the deployment of such systems.

Specifically for the PhD project, it should be noted that HOMER was proven to be an efficient but in itself limited tool in energy system modelling. Although the electrical performance of the studied systems was calculated entirely in HOMER, many thermodynamic calculations related for example to the ABS or the engine control had to be computed externally and could not influence the optimization process.

4.2. Techno-economic optimization model for polygeneration and hybrid energy storage systems (Paper III)

In order to maximise the conversion efficiency of a given biomass resource, in the following study an optimization model for a HESS with a novel dispatch control was developed. Specifically, a novel dispatch control was employed for a biogas-battery storage combination for a rural locality in Bolivia without connection to a larger national grid, which is hence working in island-mode. While the biogas can serve as a long-term storage, the batteries can cover lower electric loads and load fluctuations allowing for the biogas engine to operate at higher efficiencies. To maximize the total system efficiency, a membrane distillation (MD) unit has been considered to use recovered heat for potable water generation.

4.2.1. Case description and technical input

Based on official data from the Bolivian electricity agency (Autoridad de Fiscalización y Control Social de Electricidad) a demand profile for the locality has been created. The average monthly demand fluctuations are between -10% and +10% and the total annual electricity consumption of the village has been calculated to be 1,342 MWh [141]. The demand of one exemplary October week is presented in Figure 16. Similarly to the demand, an analysis of the available biomass resources based on the quantity of animals and humans living in the area has been conducted using data from the national statistics institute [142,143]. The total daily biogas yield has been estimated to be 593 m^3/day equivalent to 4,115 kWh/day. The conditions for solar energy have also been considered as favourable with 4.84 kWh/m^2/day [144]. The reference system is based on diesel generators, where the diesel has to be transported to the locality via trucks.

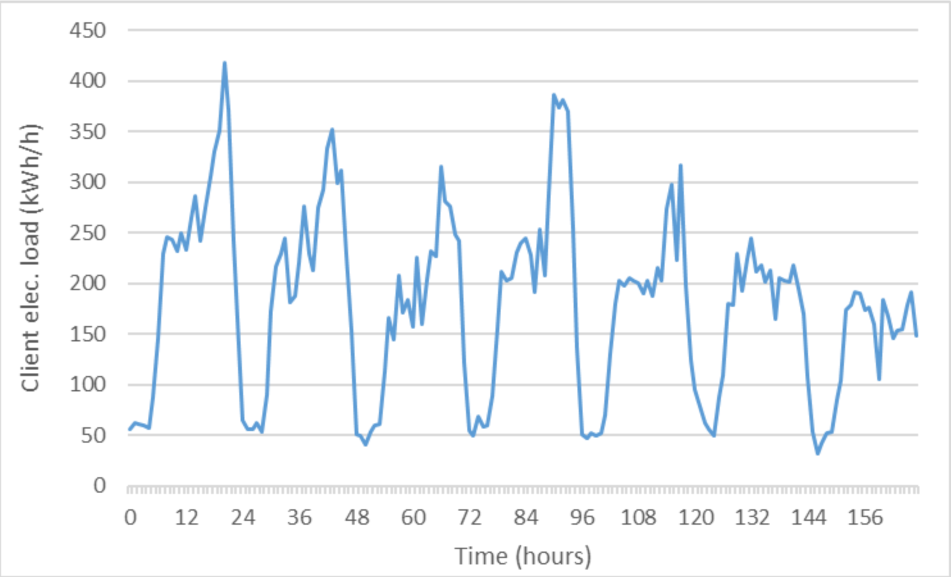


Figure 16 Electricity demand for the first week in October (Monday to Sunday)

A proposal of one polygeneration HESS layout for which the dispatch control can be used is shown in Figure 17 and a list of key technical and economic variables is given in Table *9*. Using agricultural residues and animal waste, the biogas digester produces biogas to be stored in the biogas tank and eventually to be combusted in the ICE. The generated electricity from the engine-generator couple as well as from the PV panels either serves the electricity demand of the end client directly or is stored in the batteries. A MD unit can use the recovered heat from the engine to produce high quality potable water. The heat passed on to the cooling water circuit of the MD unit can then further be used to support the anaerobic digestion process. A detailed description of the MD unit circuit is given by Khan et al. [111]. If the temperature of the jacket water cooling circuit is too high for engine entry, it can be further cooled down using an additional cooling reservoir. For the MD unit, for pumping, and for the biogas compression, a considerable amount of electricity is required, so that the combined electricity demand of the polygeneration system and the end client is higher than for the reference case. The dispatch control strategy takes this extra demand of electricity into account and decides when and how to use the engine and the batteries.

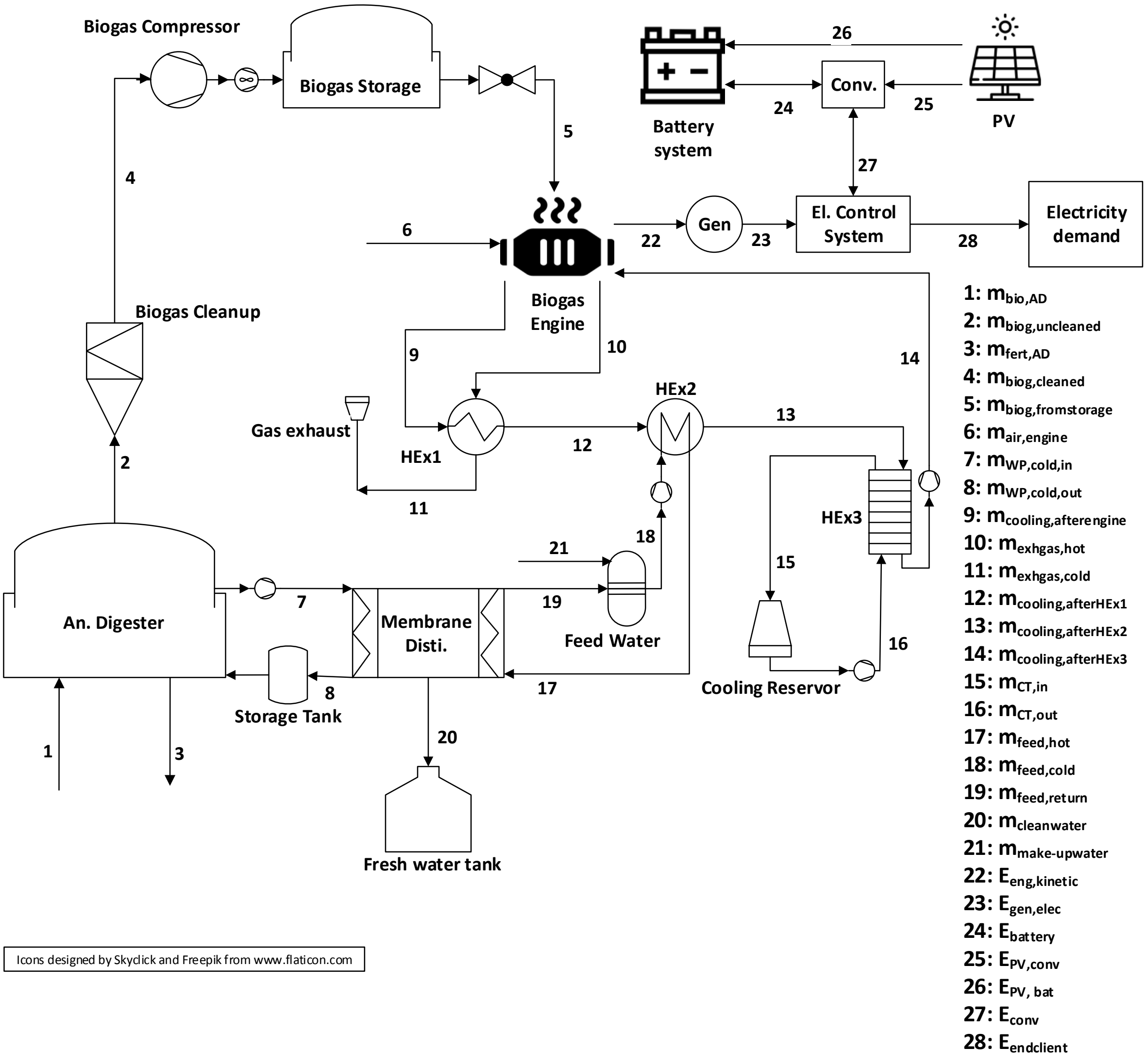


Figure 17 System sketch of a particular bio-solar polygeneration system with hybrid storage [145]

Table 9 Summary of the technical component input data

Component	Key technical and economic characteristics
Anaerobic Digester (AD) system	Biogas composition: 60% CH_4 : 40% CO_2 [111] Biogas LHV: 6.9 kWh/m^3 [146] Digester Volume: 150 Nm^3 [147] Mass transformation: 8% Biogas : 92% Slurry Capital costs (for digester, clean-up, pumps etc.): 200 USD/m^3 [147]
Biogas storage system	Dome volume: 3,840 m^3 (diameter: 21.1m, height: 15.9m) [148] Max. pressure: 20 mbar (low pressure zone) [148]
Biogas Engine CHP system	Max. electric efficiency: 38% [149,150] Recovered thermal heat: 70% (Approx. thermal efficiency of 47%) [149] Heating water outlet circuit temperature: 90°C [149] Lifetime: 15,000 h [135] Capital & Replacement costs: 200 (USD/kW) [147] O&M costs: 0.2 USD/kWh (Including AD and biogas storage system at 3,000 working hours per year) [151] Biogas price: 0.28 USD/Nm^3 (s. Chapter 2.1.2)
Water Purification system	Air gap membrane lifetime: approx. 5 years [92] Specific thermal consumption: 800 kWh/m^3 [92] Specific electricity consumption: 0.35 kWh/m^3 [92] Heat transfer to cooling circuit: 90% [92] High quality potable water price: 0.145 USD/l [152] MD unit capital & replacement costs: 390 USD/kWe (coupled to engine output) [153] MD unit attachments capital costs: 365 USD/kWe (coupled to engine output) [153]
Battery system	Generic Li-Ion battery model Depth of Discharge: 80% (equivalent to minimum SOC of 20%) [154] Approx. life cycles: 10,000 [155] Capital & Replacement costs: 1,000 USD/kWh [155]
PV system	Derating factor: 83% (equivalent to an electric efficiency of 17%) [156] Peak capacity per area: 170 W/m^2 [156] Lifetime: 25 years [156] Capital & Replacement costs: 1,800USD/kW [157] O&M costs: 10 USD/kWe/yr [157]
Diesel Engine reference system	Max. electric efficiency: 35% [158] Min. partial load: 40% [159] Lifetime: 15,000 h [160] Diesel opportunity cost: 1 USD/l [161] Capital/Replacement costs: 200 USD [162] O&M: 0.03 USD/op. hour [162]
System constraints and economics	Maximum capacity shortage $E_{cs,max}$: 1% Operating reserve: 10% Inflation rate: 4% [163] Nominal discount rate: 6% [163] Fin. reserves for uncertainties & engineering: 500 kUSD (s. Chapter 2.1.5) Project lifetime: 20 years

The optimization approach is based on the HOMER procedure, but has been augmented by connecting HOMER to the MATLAB engine, where the dispatch control has been programmed. The optimization and analysis procedure is visualized in Figure 18. The MATLAB algorithm enables three major capabilities within the HOMER environment:

1. Determination of optimal component sizes given varying biomass provision as well as fluctuating electricity demands.
2. To guarantee that the biogas engine is running whenever possible with maximum electric efficiency by using the proposed dispatch control. In turn, this ensures that the biomass is used in the most efficient way.
3. To allow for a heat demand profiled directly coupled to the engine heat generation instead of a pre-determined, rigid heat profile. Thus the engine is focused on electricity generation, but the generated heat will be used to its full potential as well. The additional electric load caused by the pumps and MD devices has been programmed as a parasitic load reducing the electricity of the engine into the control algorithm.

For an environmental comparison of the systems, the total emitted mass of carbon dioxide, $CO_{2,tot}$, has been used and calculated as follows:

$$\mathrm{m}_{\mathrm{CO2,tot}} = \mathrm{m}_{\mathrm{CO2,transp}} + \mathrm{m}_{\mathrm{CO2,comb}} \qquad (7)$$

where $\mathrm{m}_{\mathrm{CO2,transp}}$ is the mass of CO_2 emitted due to transport of biomass to the system and $\mathrm{m}_{\mathrm{CO2,comb}}$ is the mass of CO_2 emitted due to combustion. It should be noted, that biomass combustion is again considered carbon neutral.

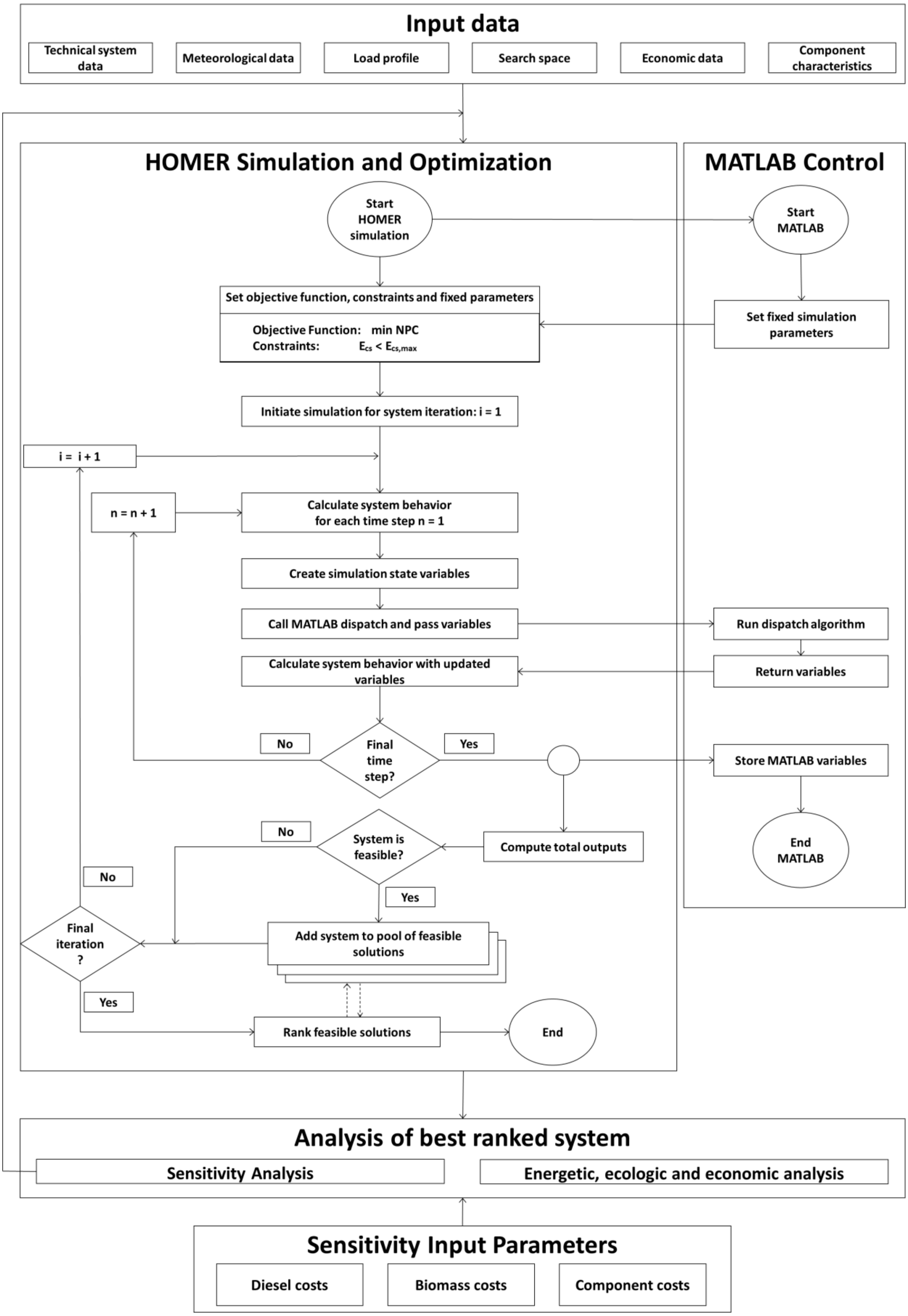


Figure 18 Optimization and analysis procedure of the best ranked system [145]

4.2.2. Main findings

Apart from white box testing, a direct comparison of the model results with previous studies has been employed to validate the dispatch control. The new dispatch (ND) control strategy has been compared with two commonly used dispatch control strategies: Electric load following (LF) and cycle charging (CC) [164]. For the cross-validation data input the same input of the study described in Paper II has been used [131]. The optimal sizes of each component are displayed in Table 10 and several key performance parameters are shown in Figure 19. The results show that the ND achieves its objective by maximising the engine electrical efficiency, however it may not be the best economic strategy when given abundant biomass as the NPC of the ND controlled system is higher than the NPC of the CC controlled system. Nonetheless, for the case study presented in Paper III the biomass supply is limited, which is why an ND control system may be favourable over other control strategies.

Table 10 Optimal component sizes of different dispatch strategies

Strategy/Comp. Size	**Bio-Eng. (kW)**	**Batteries (kWh)**	**Converter (kW)**	**PV cap. (kW)**
LF	56	317	56	85
CC	40	365	45	85
ND	46	272	40	85

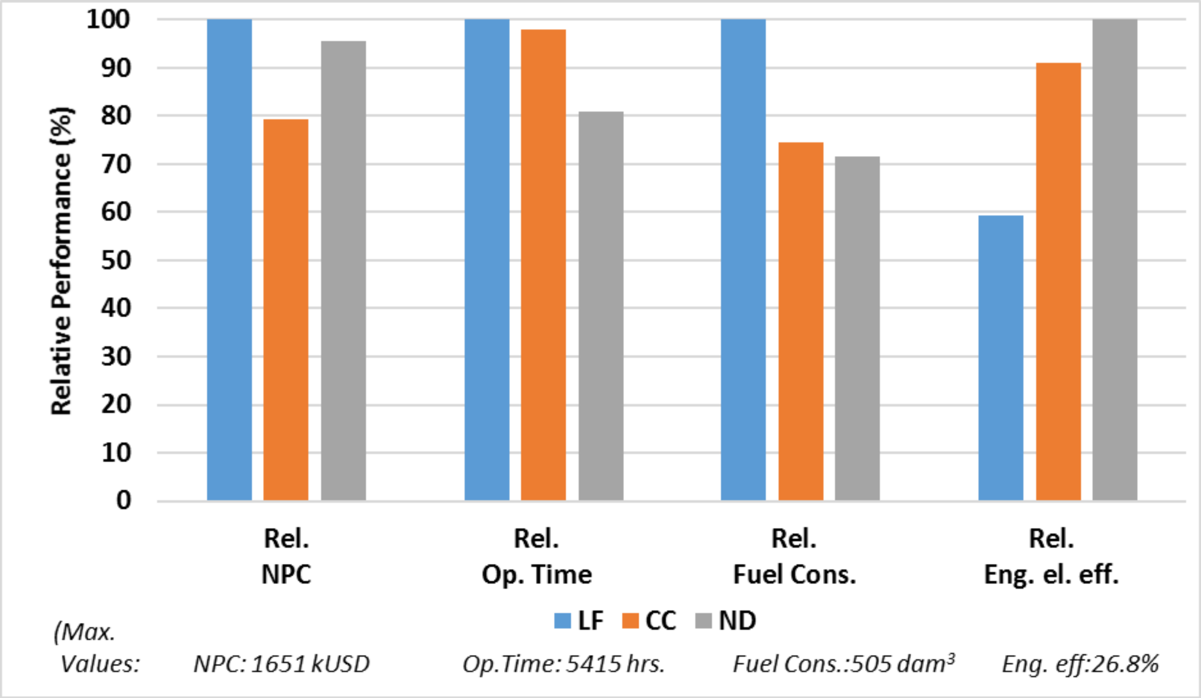
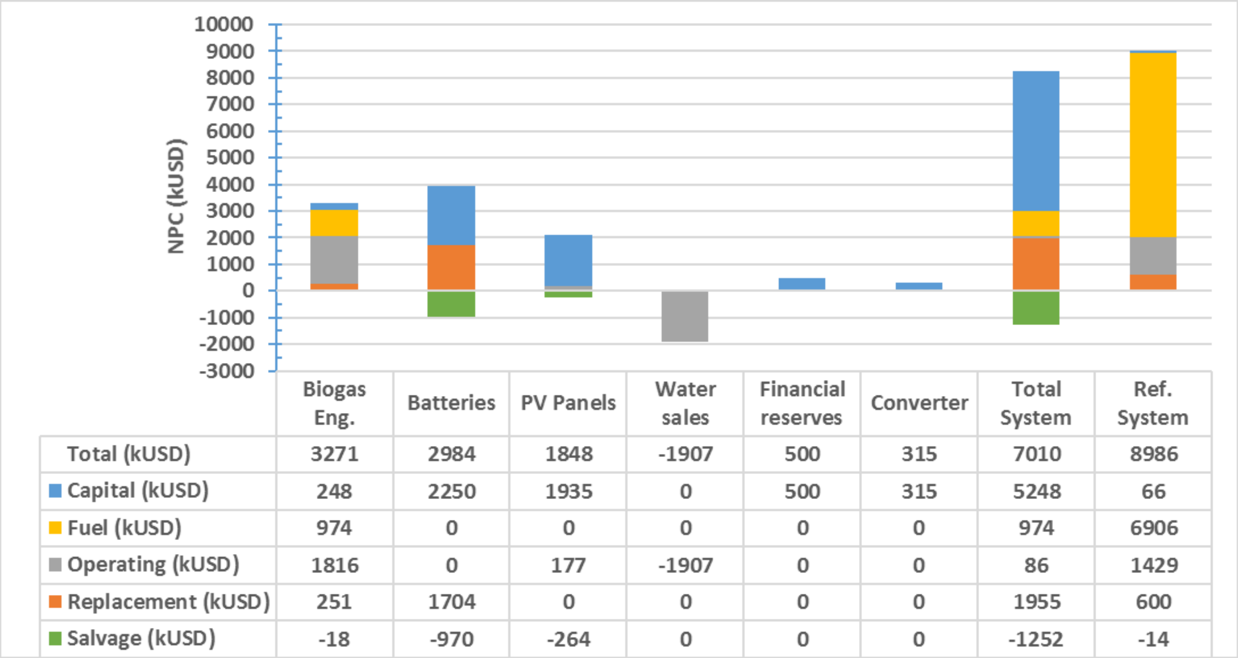


Figure 19 System and component performance for various operating strategies

The optimal size of each component as well as their yearly production and losses are shown in Table 11. With the support of the PV panels and the batteries, the engine can be downsized by nearly 20% to 260 kW compared to the reference diesel engine of 330 kW. Despite of the control dispatch aiming for maximum conversion efficiency of the biomass resources, the PV panels would have to provide 74% of the electricity. It should be noted that the PV system maximum capacity is twice as big as the conversion capacity of the converters leading to significant electricity losses. A larger converter and battery system could mitigate these losses albeit with worse economic performance. The cost structure of both the polygeneration HESS and the reference system is shown in Figure 20. The capital and the replacement costs of the polygeneration are much higher than those of the reference system, but the much lower fuel costs and the water sales lead to better project lifetime costs, so that the total polygeneration system would cost 22% less over its lifetime.

Table 11 Optimal system component parameters [145]

Component	Size	Yearly Elec. Production	Additional electricity expenses
PV system	1,075 kW (~6,320 m^2 [156])	1,602 MWh/yr (74%)	486 MWh/yr (excess)
Battery system	2,250 kWh	556 MWh/yr (annual throughput)	49 MWh/yr (losses)
Converter system	450 kW	1,876 MWh/yr (Inverter output)	138 MWh/yr (losses)
Biogas system	260 kW	554 MWh/yr (26%)	145 MWh/yr (parasitic demand)
MD unit system	Membrane area 16.7 m^2 (18 modules)	800 m^3/yr (= 2,190 l/day)	
Reference Diesel system	330 kW	1,337 MWh/yr	-



	Biogas Eng.	Batteries	PV Panels	Water sales	Financial reserves	Converter	Total System	Ref. System
Total (kUSD)	3271	2984	1848	-1907	500	315	7010	8986
🟦 Capital (kUSD)	248	2250	1935	0	500	315	5248	66
🟨 Fuel (kUSD)	974	0	0	0	0	0	974	6906
◼ Operating (kUSD)	1816	0	177	-1907	0	0	86	1429
🟧 Replacement (kUSD)	251	1704	0	0	0	0	1955	600
🟩 Salvage (kUSD)	-18	-970	-264	0	0	0	-1252	-14

Figure 20 Summary of the NPC values for the polygeneration system and the reference system [145]

Figure 21 shows how the electricity demand is satisfied by the polygeneration system for one exemplary October week. The PV panels cover the load and charge the batteries during the day, while the gas engine and the batteries cover the nightly loads. As shown in Figure 22, the ICE is operating nearly all the time at full capacity (at 260 kW_e) and hence with maximum electric efficiency as aimed for by the dispatch control. The environmental comparison of both systems has shown that the polygeneration HESS would lower CO_2 emissions of the locality's energy system by 98%. The sensitivity analysis indicates that the polygeneration HESS is much more robust towards fuel price changes and hence would increase the locality's financial autonomy immensely.

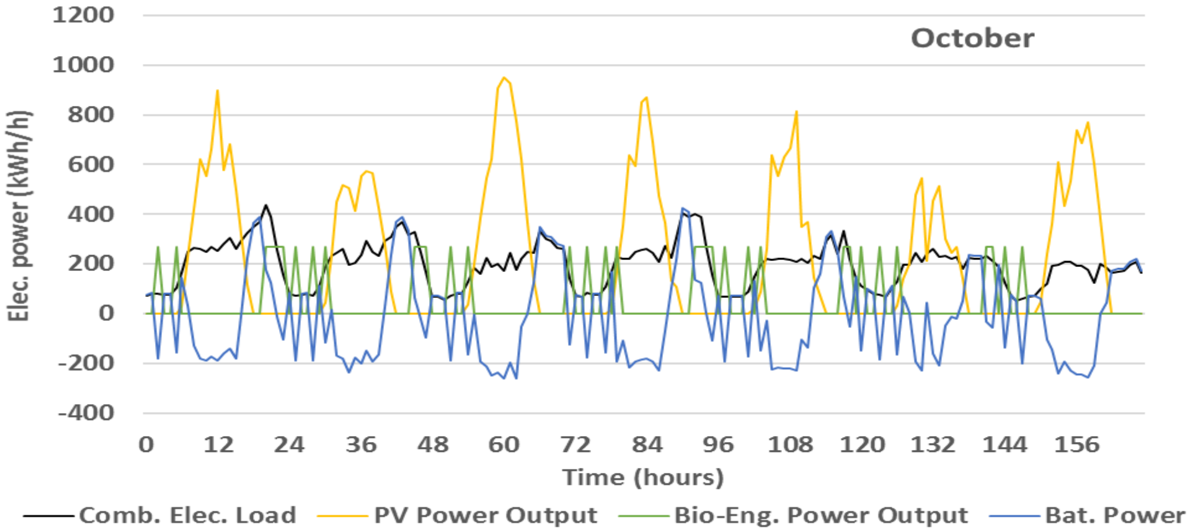


Figure 21 Electric power load and generation for one week in high demand season (October) [145]

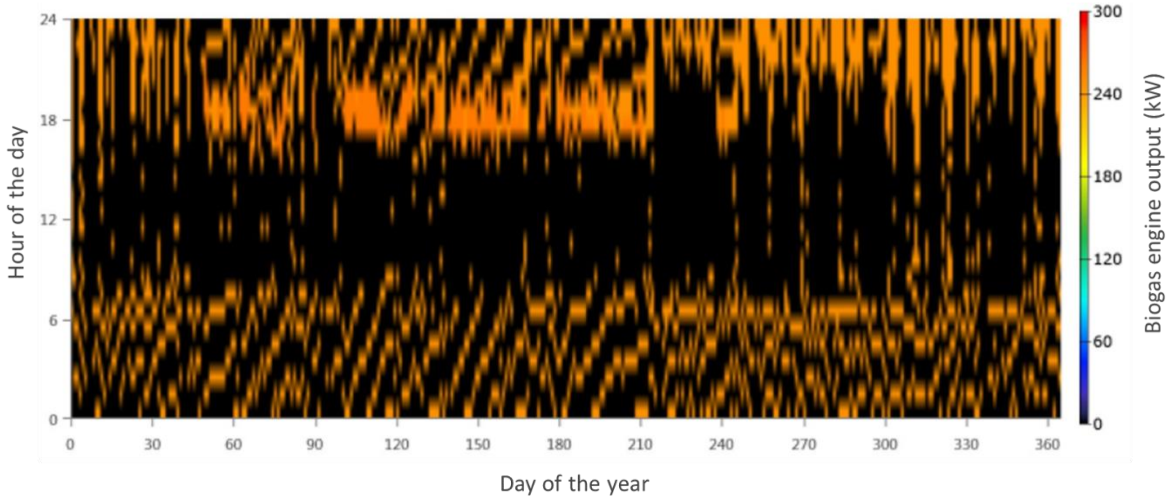


Figure 22 Biogas engine output for each hour of the year [145]

4.2.3. Concluding remarks

The study displays that even in mild climates that are unfavourable for CCHP (due to low demand for heating and cooling), a well-designed polygeneration system can still be economically viable, but can also bring more energy autonomy and decrease emissions significantly. This can be attributed to the high flexibility of the polygeneration concept, which in this study has been expressed by using recovered heat from the engine in a MD unit for potable water generation. The study also responds directly to the question on how the design and the control of a specific polygeneration system are directly coupled to each other and dictate the techno-performance of the SBP together.

The study incorporates the increasingly popular HESS concept, where the biomass works as the long-term (“marathon runner”) and the batteries as the short-term (“sprinter”) storage technologies. The direct contributions of the study to the science are the proposed modelling approach, the subsequently developed model, and the presented specific polygeneration system. All three contributions encourage the combined use of HESS and polygeneration concepts.

4.3. Techno-economic optimization model of a biomass-based CCHP/Heat Pump system under evolving climate conditions (Paper IV)

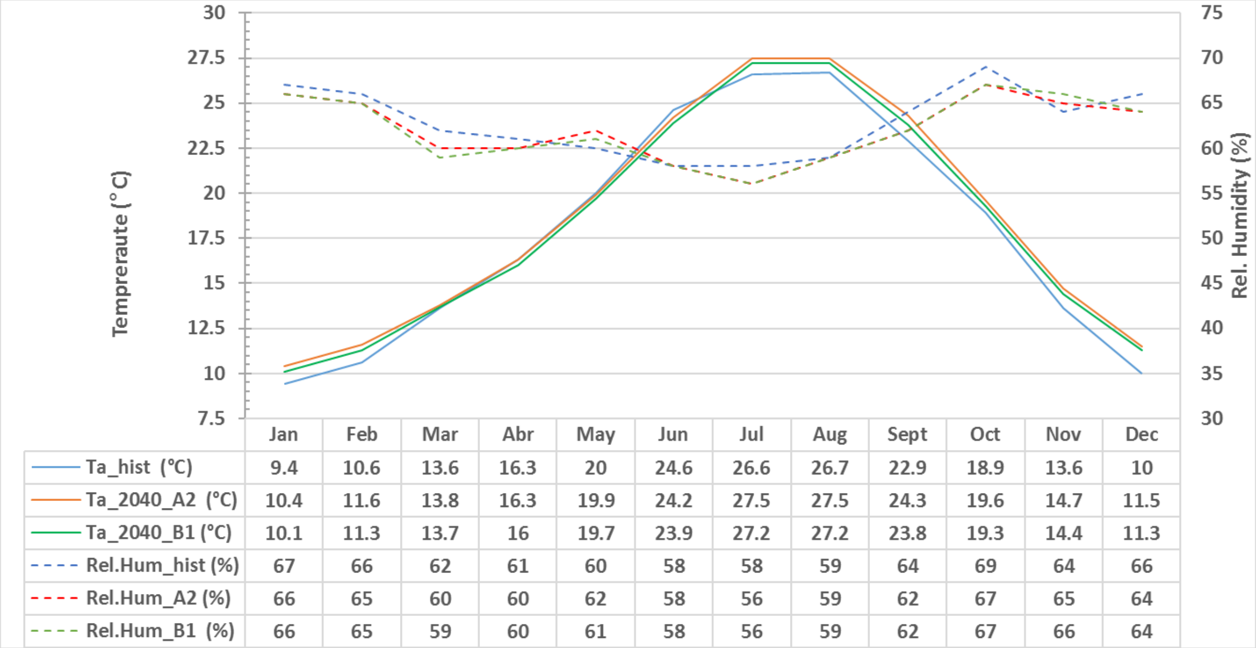
By combining a HP with a CCHP system, the following study demonstrates the flexibility of the polygeneration concept and its adaptability to other technologies. A model has been developed to allow for cost-optimal sizing of combined CCHP/HP system. The model also puts a focus on the implications of climate change for the design and sizing of such systems. Based on the developed model, a case study has been conducted for the Montjuic castle of Barcelona, where currently a museum is open for visitors and where the construction of a small residence is planned for long-term guests.

4.3.1. Case description and technical input

Three climate scenarios have been considered for analysis, which are defined as:

1. Historic scenario using climate data from 1990-2010
2. High climate change scenario (A2) using synthesized from the 4th IPCC report for a future scenario in 2040 [165]. The A2 scenario is marked by a high and steady population rise with slow technological change with more extreme consequences for climate change.
3. Low climate change scenario (B1) using synthesized from the 4th IPCC report for a future scenario in 2040 [165]. The B1 scenario is marked by steady population growth peaking at mid-century, a continuous transformation towards more service and information oriented economies, and by increasing introduction of clean and resource efficient technologies. The B1 scenario has been chosen as an alternative to the A1 scenario, where more global policies supporting more renewable and efficient technologies are implemented.

The monthly average ambient air temperature and relative humidity of each scenario are displayed in Figure 23. Comparing the A2 scenario to the historic scenario, the ambient air temperature differs most in December with 1.5°C difference implying less heating demand during this season for the A2 scenario. However, also in summer for the A2 scenario the ambient air temperature is nearly 1°C warmer in July indicating higher cooling demands during this season. For most cases the B1 scenario has ambient air temperatures somewhere in between the other two. It can also be observed that the average relative humidity is mostly higher for the historic scenario, so that more energy for dehumidification will be demanded in this scenario.



	Jan	Feb	Mar	Abr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ta_hist (°C)	9.4	10.6	13.6	16.3	20	24.6	26.6	26.7	22.9	18.9	13.6	10
Ta_2040_A2 (°C)	10.4	11.6	13.8	16.3	19.9	24.2	27.5	27.5	24.3	19.6	14.7	11.5
Ta_2040_B1 (°C)	10.1	11.3	13.7	16	19.7	23.9	27.2	27.2	23.8	19.3	14.4	11.3
Rel.Hum_hist (%)	67	66	62	61	60	58	58	59	64	69	64	66
Rel.Hum_A2 (%)	66	65	60	60	62	58	56	59	62	67	65	64
Rel.Hum_B1 (%)	66	65	59	60	61	58	56	59	62	67	66	64

Figure 23 Monthly average air temperatures and humidity for all three scenarios [166]

Apart from the climate data, information on the building structure within the Montjuic castle has been collected. Some key data on the buildings structure is given in the Annex. Using the climate and building structure data as inputs for the DM, the thermal and electric demands have been calculated. The results of the thermal demand of the demand analysis for the historic scenario are visualized in Figure 24, whereas Table 12 shows the total sums of all thermal demands. Cooling energy is not just required for space cooling but also in considerable amounts for dehumidification due to the humidity of the local climate. The demand for heating in the historic scenario is nearly three times as much as the demand for cooling, while for the A2 scenario the total yearly heating demand is more than 10% lower. On the contrary, for summery the cooling demand in the A2 scenario is up to 15% higher compared to the historic scenario. Due to the continuing demand DHW, there is also a constant need for heating during all of the year. As the structure is open nearly all days during the whole year, the electric demand for non-thermal services has been considered constant during of the year with a slightly decreased demand on the weekend due to less administration workers coming as shown in Figure 25.

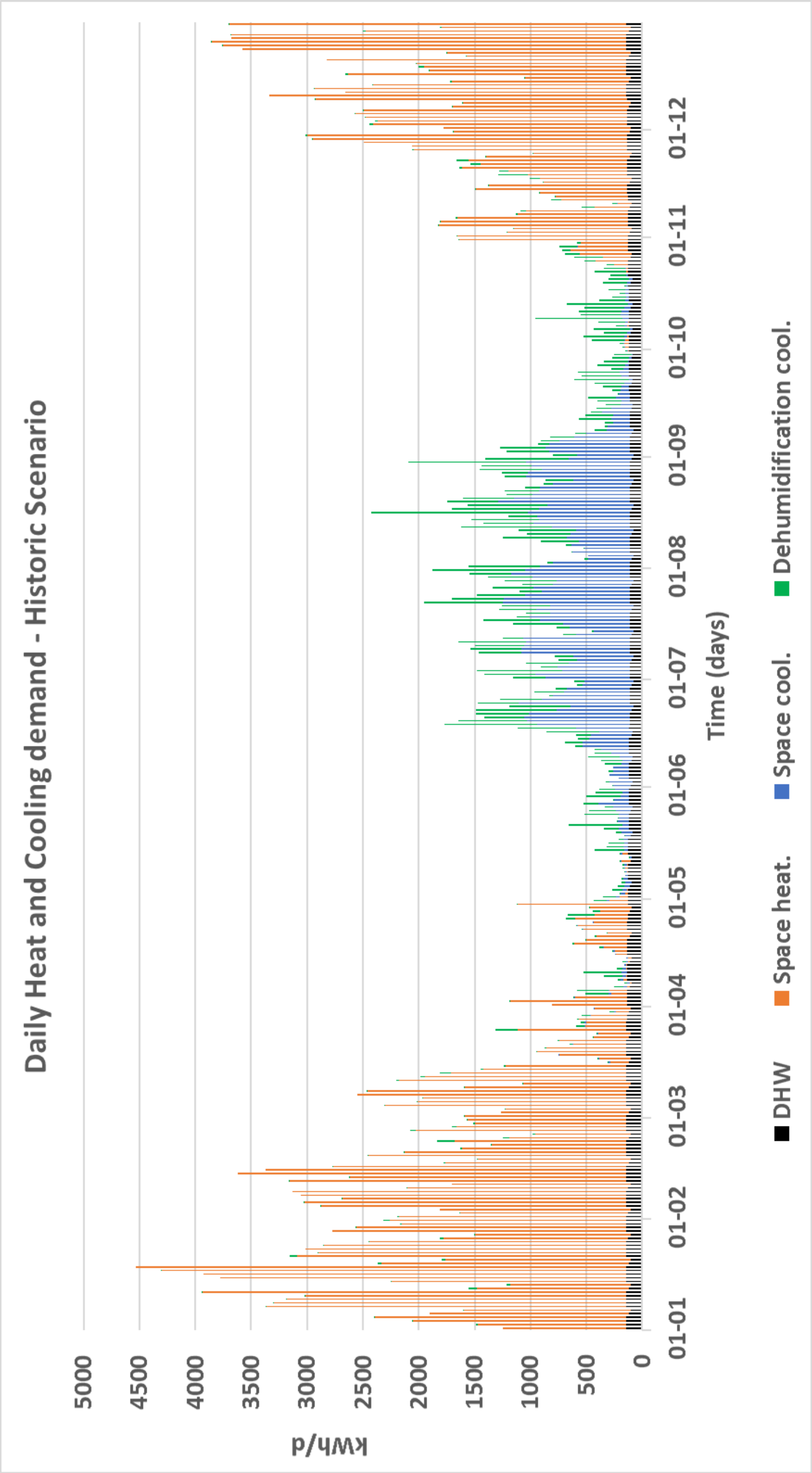


Figure 24 Daily thermal energy demands for the historic scenario [166]

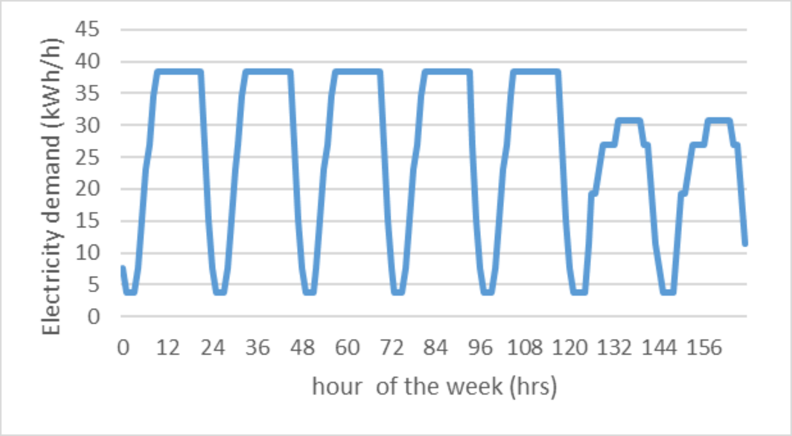


Figure 25 Electricity demand for non-thermal appliances for one exemplary week in January [166]

Table 12 Total thermal demand and peak thermal demand for all three scenarios [166]

	Heating - Hist	Cooling-Hist	Heating –A2	Cooling-A2	Heating - B1	Cooling-B1
Annual thermal demand (MWh/y)	331.9	120.8	292.5	138.4	311.6	132.5
Peak hourly demand (kWh/h)	454.2	177.0	427.1	185.7	441.7	200.9

Based on the general modelling approach shown in Figure 5, a more specific modelling approach has been developed, which is presented in Figure 26. For the demand model (DM) and the supply model (SM) the FORTRAN-based engineering software TRNSYS 17.02 has been used, which allows for the simulation of highly complex and transient energy systems [41]. For the DM, the TRNBUILD extension has been used, which calculates the physical behaviour for multiple zones of the given buildings. To start the various iterations of the SM and the post-processing of the TRNSYS results in the EM, a MATLAB environment [42] has been created, which starts the TRNSYS engine for each iteration.

Several parameters have been selected for 3E-comparison of each iteration [166]:

1. For the energetic performance of each CCHP iteration, the CCHP system efficiency η_{CCHP} has been calculated as follows:

$$\eta_{CCHP} = \frac{Q_{heat} + Q_{cool} + E_{el,CCHP}}{m_{bio} \times LHV} \tag{8}$$

where Q_{heat} is the heating energy, Q_{cool}, is the cooling energy, and $E_{el,CCHP}$ is the electric energy supplied by the CCHP system, while m_{bio} is the biomass supplied to the system and LHV is the lower heating value of the biomass. The COP and the Energy Efficiency Ratio (EER) of the HP have been determined as follows:

$$COP = \frac{Q_{heat,HP}}{E_{hp,h}} \tag{9}$$

$$EER = \frac{Q_{cool,HP}}{E_{hp,c}} \tag{10}$$

where $Q_{heat,HP}$ and $Q_{cool,HP}$ are the heating and cooling energy provided by the HP with $E_{hp,h}$ and $E_{hp,c}$ being the electric energy provided to the HP for heating and cooling, respectively.

2. For the economic comparison the NPC has been used defined in equation (1).

3. To compare the environmental impact the total CO2-eq emissions have been used by combining the emissions of the sub-systems as follows:

$$CO_2eq,t = sCO_2eq_b \times E_{el,CCHP} + sCO_2eq_{grid} \times E_{el,grid} \tag{11}$$

where CO_2eq,t are the total CO2-eq emissions of the system, sCO_2eq_b and sCO_2eq_{grid} are the specific CO2-eq emissions of the biomass system and the electric grid, respectively, and $E_{el,grid}$ is the electric energy supplied by the grid.

Whenever the system can sell excess electricity avoided emissions occur, which have been computed as follows:

$$CO_2eq,t_{av} = sCO_2eq_b \times E_{el,CCHP,i} + sCO_2eq_{grid} \times E_{el,grid} - E_{el,CCHP,e} \times (sCO_2eq_{grid} - sCO_2eq_b) \tag{12}$$

where CO_2eq,t_{av} are the total CO2-eq emissions of the system including avoided emissions, $E_{el,CCHP,i}$ is the electric energy supplied by the CCHP system for internal consumption and $E_{el,CCHP,e}$ is the electric energy supplied by the CCHP system for external consumption assuming it replaces grid energy.

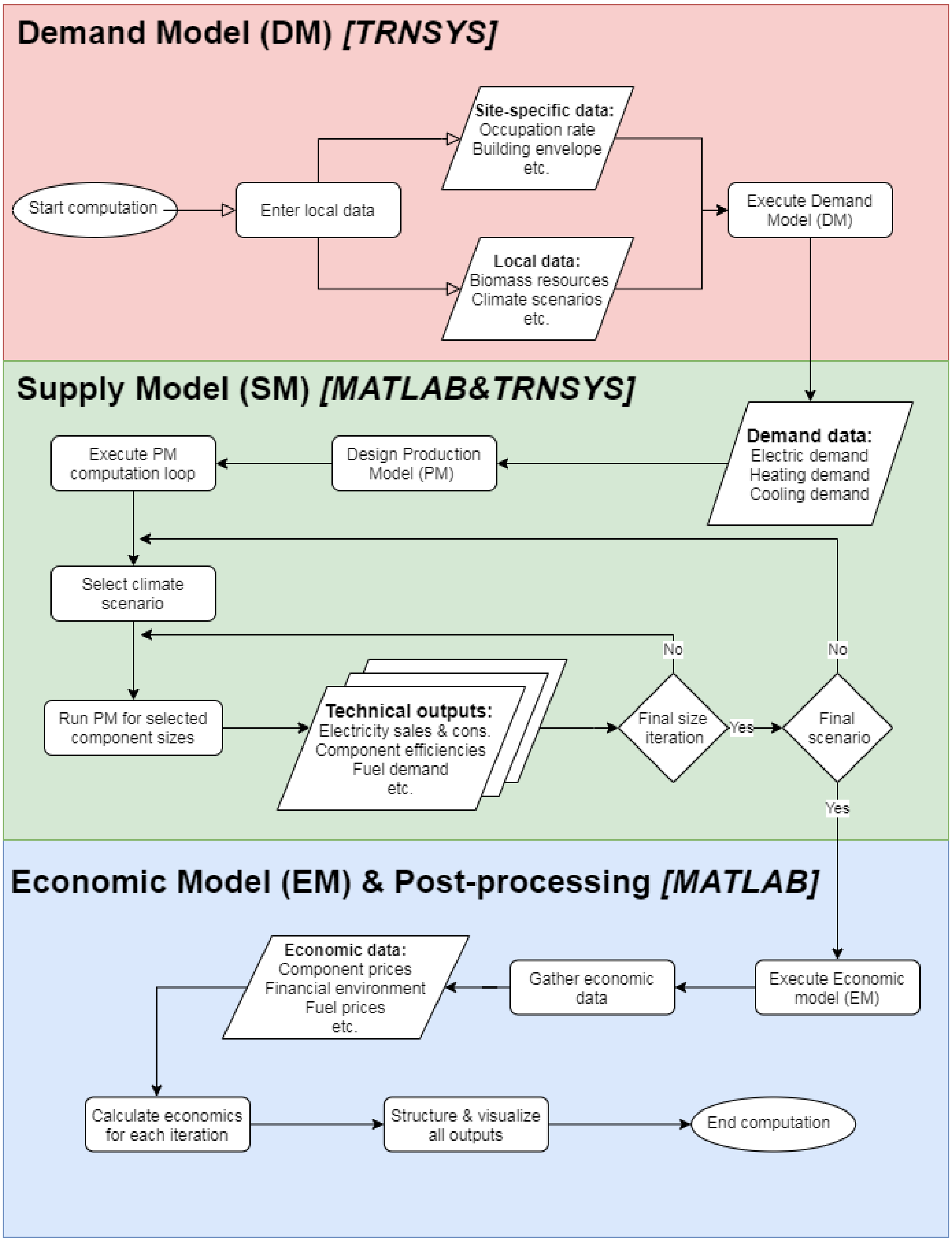


Figure 26 Modelling approach of CCHP/HP systems for various climate change scenarios [166]

Using the results of the DM, a CCHP/HP system has been designed with the primary objective that both sub-systems can operate independently from the other. The designed system is displayed in Figure 27. The CCHP system is fuelled by syngas produced by a downdraft gasifier, which itself is fuelled by locally available wood chips. Before engine entry, the syngas is filtered and cooled down by various clean-up units. After fuel combustion, the kinetic energy of the engine is transformed to electric energy via a generator and used for system internal demands, stored in the batteries, supplied to the end client, and/or sold to the external electric grid. The model can take into account additional electricity served by PV panels, although for the case study the PV panel capacity has been set to only 20 kW_e, because no larger area suitable for PV panel placement has been identified. An electric load following control algorithm, which has been identified as one of the most suitable strategies for Mediterranean climates [116], has been used:

1. If batteries and PV panels can supply sufficient electricity, the engine is turned off.
2. If batteries and PV panels cannot supply sufficient electricity, the engine is:
    a) Set to minimum partial load, if the electricity demand after PV panel supply is equal or lower than partial load. Excess electricity from the engine is stored in the batteries and/or, in case the batteries are fully charged, sold to the grid.
    b) Set to the remaining load, if the electricity demand after PV panels is in between minimum partial load and maximum capacity of the engine
    c) Set to maximum capacity, if the electricity demand after PV panels and batteries exceeds the maximum capacity. All remaining demanded electricity is drawn from the electric grid.

The engine exhaust gases after combustion transfer some of their heat to the engine jacket water coming out from the engine in Heat Exchanger 1 (HEx1). Afterwards, the jacket water transfers its heat to a hot water circuit in Heat Exchanger 2 (HEx2). In case the jacket water is too hot for engine cooling, a post-cooler cools it down to 80°C. In case, cooling is needed, the hot water drives an absorption chilling process within an ABS. Otherwise, the hot water circuit transfers heat to the end client and then any remaining heat afterwards is stored in a hot water tank. Similarly, the chilled water from the ABS provides cooling power to the end client. During summer months, a cooling tank is employed to store chilled water whenever the ABS can produce excess cooling. Whenever, the heating and cooling supply of the CCHP system is not sufficient, the air-sourced HP (ASHP) is employed to provide any missing thermal energy. The cooling capacity of the ABS has been set equal to the electricity generation capacity of the engine as with this relationship the engine exhaust heat can satisfy the ABS heat demand during full load.

A list of key technical and economic parameters used as input data are shown in Table 14 and Table 15. For most components a linear relationship between costs and capacity has been regarded as sufficiently accurate. However, for the investment costs of the ABS a logarithmic function based in national data has been used [114,167]:

$$\mathrm{I_{Abs}} = -236.5\,€ \times \ln(\mathrm{maxCap}) + 1{,}655.4\,€ \tag{13}$$

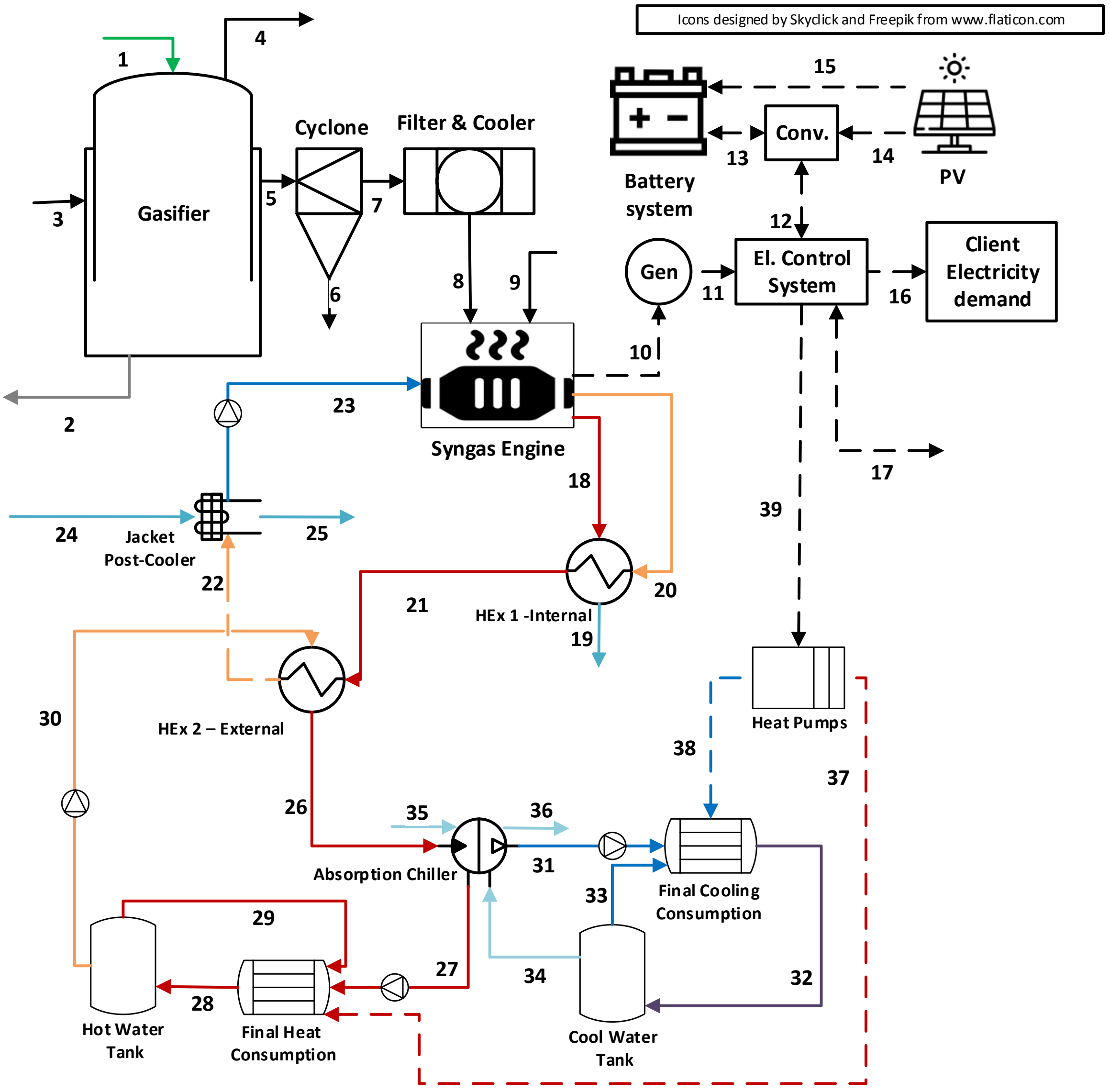
where I_{Abs} is the installation costs per base capacity unit (in €/kWt) and maxCap is the absorption chiller maximum capacity. For the electricity costs a dynamic price structure based on data provided by the local administration has been used. A summary of prices and emissions for electricity and biomass is given in Table 13.

Table 13 Prices and emissions for electricity and biomass input

Electric grid*	Flexible electricity consumption costs: off & flat & peak	62.66 €/MWh & 82.08 €/MWh & 94.52 €/MWh
	Electric capacity costs	0.009477€/(kW_{cap}•h)
	Taxes: Electricity & VAT	5.1% & 21%

	Electricity selling price	5.00 €/MWh [168]
	CO_2-emissions – Spanish grid - sCO_2eq_{grid}	265.5 g CO_2/kWh_e [169]
Biomass	Pre-treated wood splinter costs	90 €/t [170]
	CO_2-emissions – Gasification - sCO_2eq_b	45 g CO_2/kWh_e [58]

*All electricity costs are based on electricity bills from 2018-2019



1: $m_{biomass}$
2: $m_{gasifier,ash\&char}$
3: $m_{gasifier,air}$
4: $m_{gasifier, exhaust gas}$
5: $m_{gasifier,syngas}$
6: $m_{cyclone,chars}$
7: $m_{cyclone,syngas}$
8: $m_{syngas,intake}$
9: $m_{air,intake}$
10: $E_{eng,kinetic}$
11: $E_{gen,elec}$
12: $E_{conv,system}$
13: $E_{bat,conv}$
14: $E_{PV,conv}$
15: $E_{PV, bat}$
16: $E_{el\_con,endclient}$
17: $E_{el, grid}$
18: $m_{eng,exhaust,hot}$
19: $m_{HEx2,exhaust,cool}$
20: $m_{eng,afterEngine}$
21: $m_{eng,afterHEx1}$
22: $m_{eng,afterHEx2}$
23: $m_{eng,toEngine}$
24: $m_{cooling,before}$
25: $m_{cooling,after}$
26: $m_{hotw,afterHEx2}$
27: $m_{hotw,afterABS}$
28: $m_{hotw,afterCons}$
29: $m_{hotw,tanktoCons}$
30:$m_{hotw,tanktoHEx2}$
31: $m_{chillw,AbstoCons}$
32: $m_{chillw,toTank}$
33:$m_{chillw,TanktoCons}$
34: $m_{chillw,TanktoAbs}$
35:$m_{coolw,toAbs}$
36: $m_{coolw,fromAbs}$
37:$Q_{hp,heat}$
38: $Q_{hp,cool}$
39: $E_{el\_con,system}$*

*Including all other machinery

Figure 27 System sketch for the combined CCHP and HP system [166]

Table 14 Key technical parameters [166]

Subsystem	Component characteristics	Component parameter
Downdraft Gasifier	Biomass type	Woodchips
	Biomass LHV (dry basis)	5.5 kWh/kg [171]
	Gasifier efficiency (wood to syngas)	~ 75% [136]
	Lifetime	10 years [172]
Engine	Engine max. electric efficiency	22.4% [66,173]
	Engine max. thermal efficiency	67.5% (s. supplementary data)
	Engine min. partial load	40% [173]
	Engine jacket water max. entry temperature	80 °C [174]
	Engine jacket water specific heat	3.6 kJ/kg/K
	Lifetime	5 years [172]
Absorption Chiller	Component size	Equal to engine size
	Reference max. COP	0.8 [175]
	Hot water input max & min. temperature	110°C & 80°C [175,176]
	Chilled water exit & return temperature	7°C & 12°C [175,176]
	Cooling water inlet temp./ amb. water temp.	~16-35 °C
	Lifetime	20 years [177]
Air-sourced HPs	Refrigerant medium	R134a [178]
	Reference COP (heating) & EER (cooling)	3.3 & 2.8 [178]
	Lifetime	20 years [179]
Batteries & Converter	Type	Lead-acid
	Converter power per energy stored	0.5 W/Wh [154]
	Invertor & Regulator efficiency	96% [157]
	Lifetime	10 years [154]
	Max. storage capacity	50 kWh
PV panels	Type	Polycrystalline
	Max. efficiency	17% [156]
	Lifetime	>20 years [180]
	Set max. PV nominal capacity	20 kW_e
Storage tanks & Pumping	Storage volume: hot & cold	15 m^3 & 10 m^3
	Temperature range: hot & cold	60-90 °C & 7-12 °C
	Tank height & geometry	4m & cylindrical
	Heat transfer coefficient	1 $kJ/K/hr/m^2$
	Electricity demand for pumps	45.5 $Wh/kg_{water}/m_{height}$ [181]
	Average pump height	10 m

Table 15 Key economic inputs [166]

Subsystem	Components	Component costs	O&M costs*
Gasifier and CHP system	Biomass drying & pre-processing	1,500 €/kW$_e$	100 €/kW$_e$ /yr[151,182]
	Gasifier	3,700 €/kW$_e$	
	CHP system	1,330 €/kW$_e$	
	Component Transport & Control system	100,000 €	
Battery system	Batteries and cell connections	450 €/kWh	25 €/kW$_e$/yr [154]
	Additional battery hardware (transformers, controllers, etc.)	100 €/kWh	
Absorption chiller	Component, Engineering, Installation, etc. costs	s. equation (13)	0.01 €/kWh [85]
Photovoltaic system	PV panels	600 €/kWp	50 €/kW$_e$/yr [157]
	Auxiliary structure	600 €/kWp	
	Additional PV hardware (regulators, insulation, monitoring, etc.)	300 €/kWp	
Retrofitting of technical rooms and access (Lluneta de Mar)	Exterior envelope (isolation, waterproofing, wall restoration, etc.)	200,000 €	-
	Interior envelope (ventilation, restoration of interior rooms, service rooms, electric connections, etc.)	350,000 €	
	Reformation of surroundings (trench opening, pathways, etc.)	50,000 €	
	Connections and adaptions to existing system (civil works, tubing, electric connections, etc)	250,000 €	
Heat pumps	Component and installation costs	700 €/kW	Neglected [179]
Financial environment	Capital reserves for the sum of all assets	7.5%	-
	Replacement costs of all components	70%	-
	Real discount rate	4% [183]	-
	Project lifetime	20 years	-

*Replacement costs are calculated separately.

4.3.2. Main findings

The relationship between CCHP and HP size is shown in Table 16. Logically, the larger the CCHP the lower the necessary HP size and the lower the grid purchases, while grid sales increase with the engine generating more often excess electricity. With an engine size of 150 kW$_e$, the energy demands of the castle structure could be satisfied without any external electricity. The efficiency of various sub-systems are visualized in Figure 28. With rising CCHP size, the thermal efficiency of the CCHP system drops because less of the recovered heat can be used directly for end client purposes and is hence lost to the environment. Compared to an only-HP system, the installation of a CCHP setup reduces the efficiency of the HP, both for cooling and for heating as the HP unit is used less during transitions seasons, where its efficiency is generally higher. For larger CCHP layouts, the engine operates less often and hence the ABS receives less often sufficient heat for operation. Therefore, here the

HP is used more often for cooling (and specifically for dehumidification) and also during the transition and winter months, which is when the EER is comparatively high.

Table 16 Component sizes, operation time and grid exchanges for the historic case [166]

Engine		**ABS**		**HP**		**Grid purchases**			**Grid sales**		
Size (kW$_e$)	**Op. hrs**	**Size (kW$_e$)**	**Op. hrs**	**Size (kW$_e$)**	**Op. hrs**	**Energy (kWh)**	**Cap. (kW)**	**Op. hrs**	**Energy (kWh)**	**Cap. (kW)**	**Op. hrs**
0	0	0	0	173	8,743	382,910	214	8,764	0	0	0
25	8,120	25	4,844	125	2,527	76,069	125	4,508	0	0	0
50	7,515	50	4,732	84	2,001	4,783	61	486	2,451	8	843
75	7,200	75	4,365	71	1,995	531	24	74	21,323	20	2,443
100	7,084	100	4,257	108	1,790	285	38	28	64,769	30	4,280
125	7,052	125	4,340	90	1,352	31	22	3	128,184	40	6,012
150	7,027	150	4,393	120	909	0	0	0	198,683	50	6,716
175	7,032	175	4,444	105	634	0	0	0	271,076	60	6,887
200	7,027	200	4,479	78	479	0	0	0	343,370	70	6,980

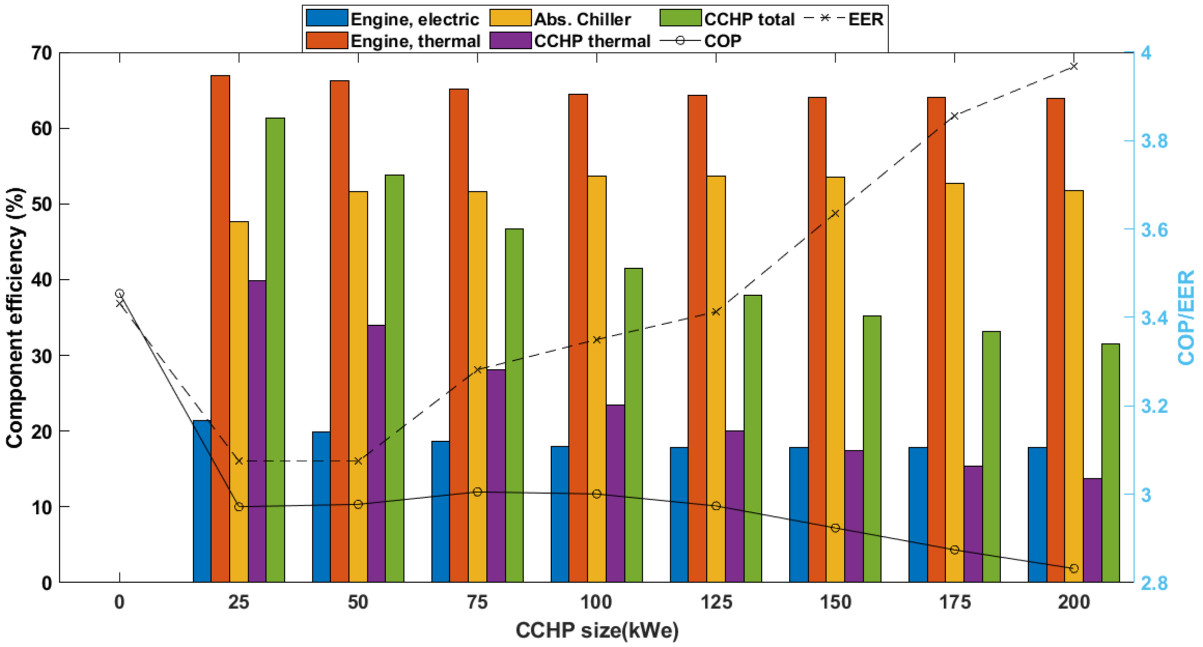


Figure 28 Component and system efficiency for different CCHP sizes [166]

A comparison of the HP and CCHP system efficiencies for the different climate scenarios is shown in Figure 29. For almost all CCHP system sizes, the high climate change requires less HP capacity, although the CCHP system efficiency is for all sizes at least 2% lower. Both these phenomena can be attributed to the decreased heat demand in the A2 scenario, especially in winter.

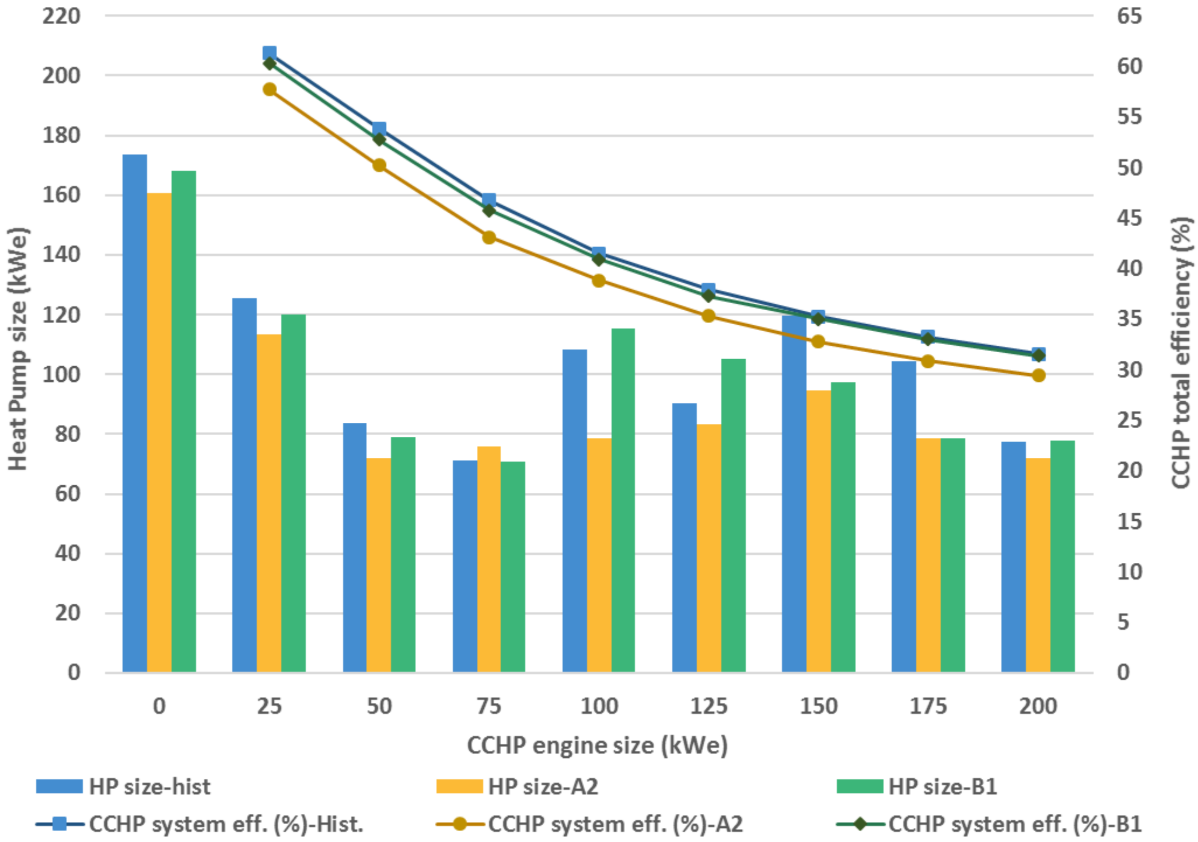


Figure 29 Energetic system performances for different climate scenarios [166]

The economic performances of the only-HP and the different sized CCHP/HP systems for the historic scenario are presented in Figure 30. For the only-HP system the electricity costs outweigh the capital costs, while when adding a CCHP system of any size the fuel costs are reduced significantly. However, only a small 25 kW_e CCHP system would lead to lifetime cost reductions, as all CCHP systems require high capital investment. The small CCHP system would lead to cost-reductions of more than 7%. The impact of climate change on the system design and component sizing is diminutive as can be observed from Figure 31. In an all climate scenarios the combination with the smallest CCHP system of 25 kW_e outperforms all other options.

The CO_2 emissions for the historic scenario are shown in Figure 32. The larger the CCHP system the higher the emissions due to biomass (incl. harvesting and transport), however also more emissions would be avoided as less electricity from the national grid would be purchased and cleaner electricity would be sold to the grid. Interestingly, the high climate change scenario would lead to lower emissions for all CCHP system sizes as shown in Figure 33.

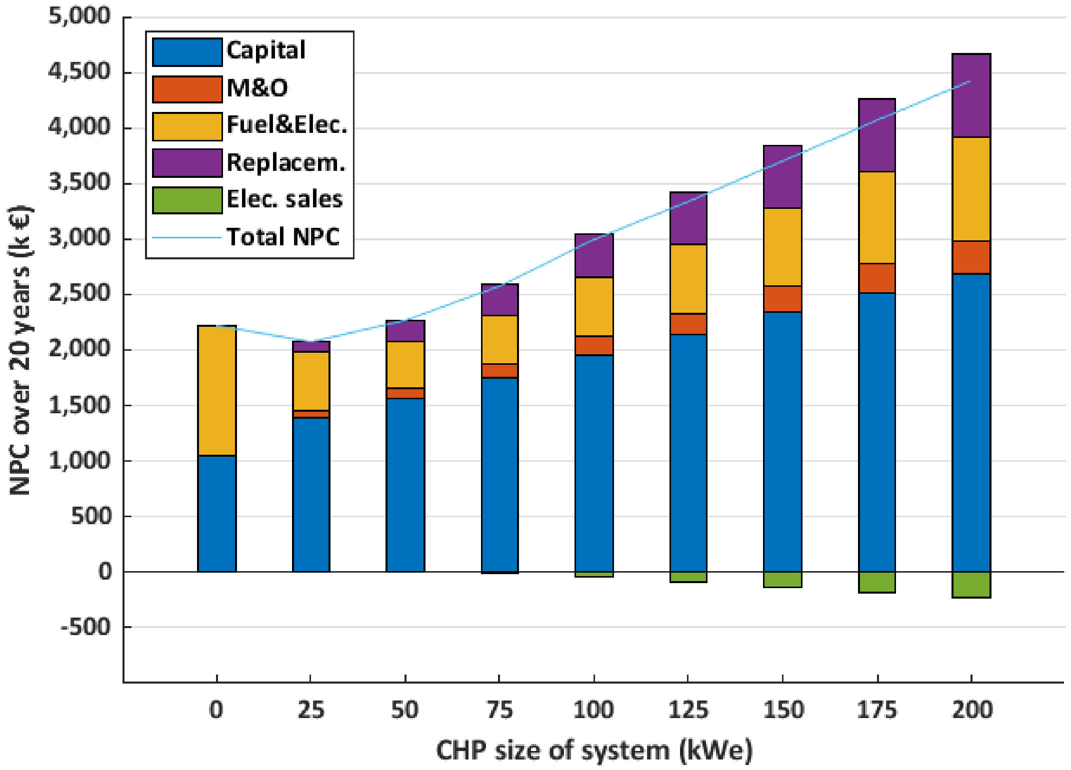
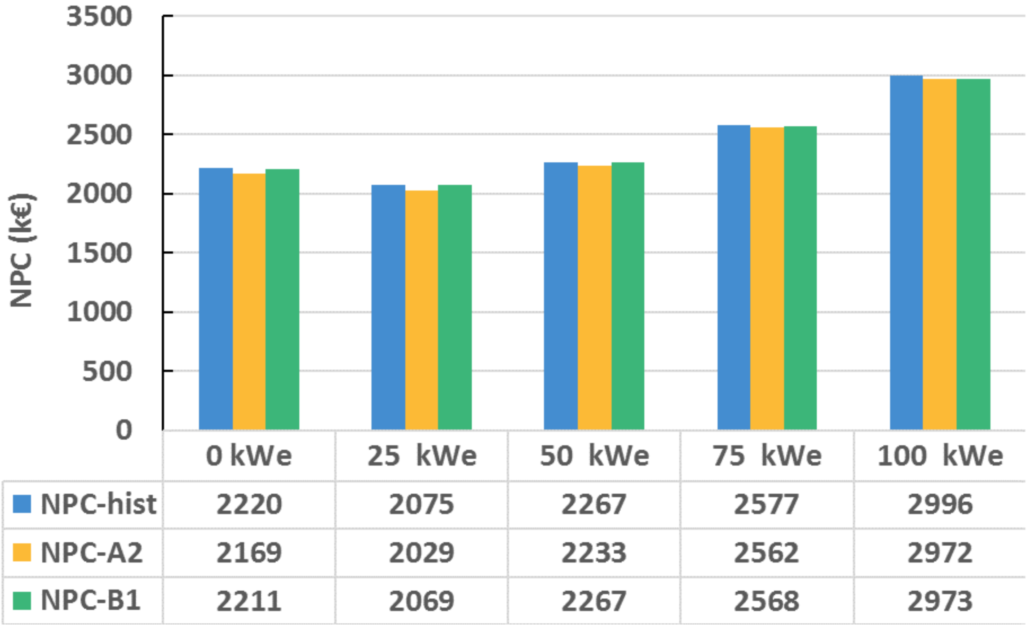


Figure 30 NPC of components and the total system for the historic scenario [166]



	0 kWe	25 kWe	50 kWe	75 kWe	100 kWe
🟦 NPC-hist	2220	2075	2267	2577	2996
🟨 NPC-A2	2169	2029	2233	2562	2972
🟩 NPC-B1	2211	2069	2267	2568	2973

Figure 31 NPC of CCHP system up to 100 kWe for all climate scenarios [166]

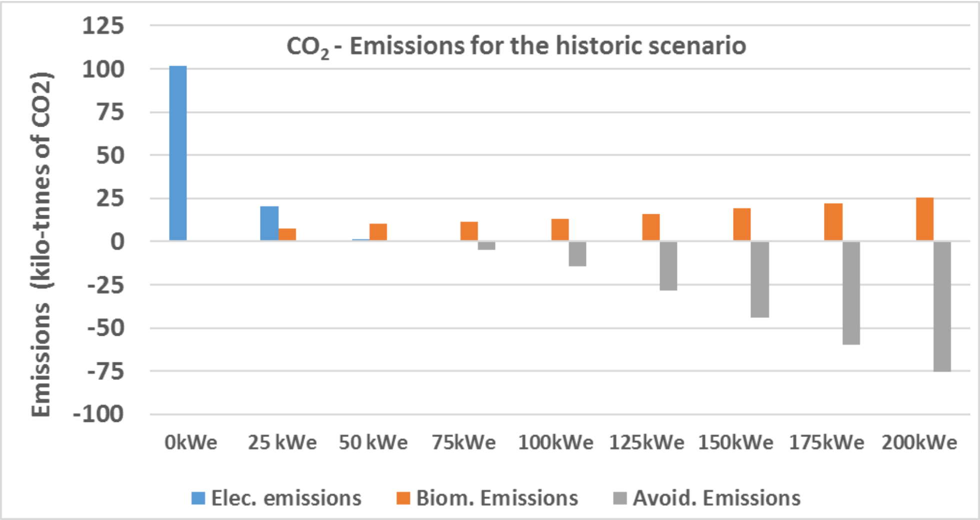


Figure 32 CO_2 emissions for the historic scenario for all CCHP sizes [166]

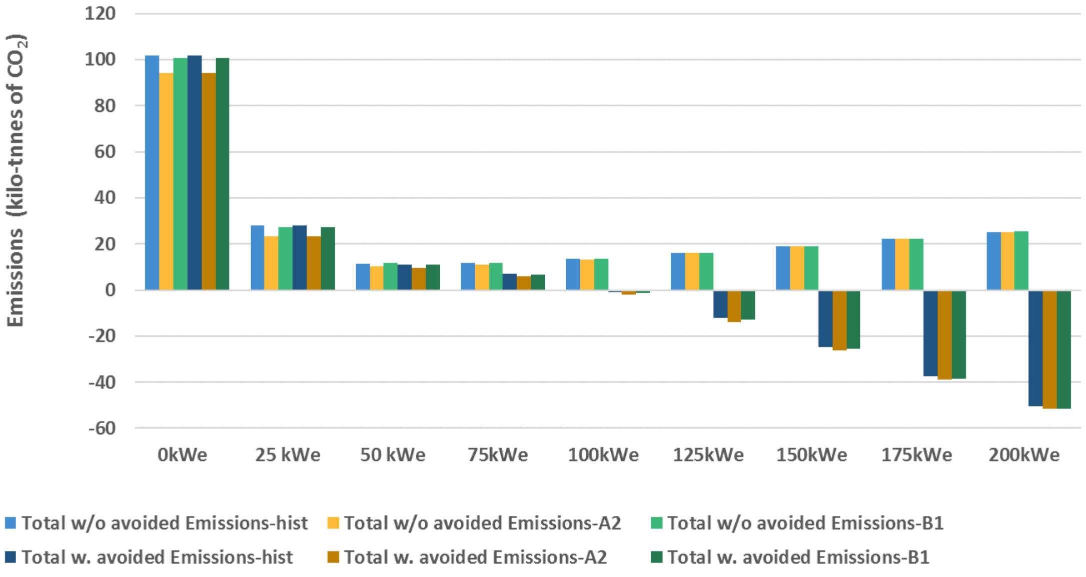


Figure 33 CO_2 emissions for all scenarios and for all CCHP sizes with and without avoided emissions [166]

4.3.3. Concluding remarks

The proposed CCHP/HP system, which also includes batteries and PV panels, proofs the adaptability of the polygeneration concept towards other technologies. Furthermore, it shows how a combined CCHP and HP system can outperform an already efficient only-HP system. However, the relatively small economic difference between the only-HP system and the combined approach also shows the difficult position for the polygeneration concept in urban areas. With increasingly less polluting electricity mixes and smarter electricity price schemes, the polygeneration systems may have more and tougher competition in urban areas than systems in more isolated regions. It must be noted that the study focused on the interaction between HP and CCHP with many other variables set to fixed values. The proposed model could also take into consideration various sizes of PV panel capacities, battery capacities, and storage tank volumes, but also other control strategies or even other climate regions could be investigated with the model.

The study responds to the question how climate change will impact the design and sizing of SBP. It shows that the efficiencies of various sub-systems are directly affected by rising ambient air and ground water temperatures, especially of the ABS and of the HP but also to a lesser degree of the engine and the HEx. Although it seems counter-intuitive, the warmer the future climate, the lower the efficiency of the combined system, but also the lower energy consumption and costs. This can be explained by lower efficiencies of the HP when working in summer, but much less demand for heating in winter. Nevertheless, the impact on the calculated system economics and hence on the system design is not decisive enough to alter the sizing of the components significantly.

4.4. Exergetic analysis of a small-scale CCHP/HP system based on biomass gasification (Paper V)

Using the same input data as in the study of Chapter 4.3, a similar CCHP/HP system was investigated for exergetic performance in the following study. Apart from all the equations for the exergy calculations, the model developed for this study includes also a sub-model for the chemical processes occurring in the downdraft gasifier. The methodological approach followed in this study differs only slightly from the approach of the study presented in 4.3: no scenario analysis for various climates has been conducted and the results have been post-processed for exergetic performance instead of economic performance.

4.4.1. Case description and technical input

For the case study, the same electric and thermal demand data as for the historic case of Chapter 4.3.1 has been used. However, the CCHP/HP system has been slightly altered. No storage tanks, no batteries, and no PV panels have been considered for the sake of simplification. The layout of the polygeneration is shown in Figure 34. For the computations of the exergy several assumptions have been made:

1. The dead state is defined by the ambient air temperature and hence is dynamic.
2. All gases are assumed to be ideal gases.
3. The composition has been simplified to 79% nitrogen and 21% oxygen.
4. All ashes are considered to be unreactive.
5. Tar has been excluded from the model.
6. The heat capacity of graphite has been used for the heat capacity of char.
7. Moisture in biomass is considered liquid water, which will be fully evaporated during gasification.
8. Potential and kinetic exergies have been neglected as have been exergy changes due to pressure fluctuations.

Several chemical equations are necessary for calculating the exergetic performance of the system and of the individual components. For all exergy flows the exergy has been defined as:

$$\mathrm{e} = \mathrm{e}_{\mathrm{ch}} + \mathrm{e}_{\mathrm{ph}} \tag{14}$$

The physical exergy of gases has been calculated with:

$$\mathrm{e}_{\mathrm{ph,g}} = \mathrm{c_p}\left[(\mathrm{T_i} - \mathrm{T_o}) - \mathrm{T_O} \times \ln\frac{\mathrm{T_i}}{\mathrm{T_o}} \right] \tag{15}$$

where $\mathrm{T_i}$ is the temperature of the individual gas stream i. The chemical exergy of gases has been calculated with:

$$\mathrm{e}_{\mathrm{ch,g}} = \sum_{\mathrm{i}} \mathrm{y_i} \times \mathrm{b}_{\mathrm{ch,i}} + \mathrm{RT_o} \sum_{\mathrm{i}} \mathrm{y_i} \times \ln(\mathrm{y_i}) \tag{16}$$

The physical exergy of liquids has been calculated with the following formula:

$$\mathrm{e}_{\mathrm{ph,l}} = (\mathrm{h_i} - \mathrm{h_o}) - \mathrm{T_o}(\mathrm{s_i} - \mathrm{s_o}) \tag{17}$$

For the exergy of thermal flows the following formula has been used:

$$e_q = Q \times (1 - \frac{T_o}{T_i}) \tag{18}$$

The formula of Szargut et al. [184,185] is employed to calculate the LHV of the biomass:

$$\mathrm{LHV} = e_{ch,biomass}/\beta \tag{19}$$

The values of the biomass exergy $e_{ch,biomass}$ are provided by Song et al. [186],while β is calculated as follows:

$$\beta = \begin{cases} 1.0438 + 0.1882\ \frac{w_H}{w_C} + \ 0.0610\ \frac{w_O}{w_C} + 0.0404\ \frac{w_N}{w_C}\ \text{for}\ \frac{w_O}{w_C}\ \leq 0.5 \\ \beta = \frac{\left[1.0438+0.1882\frac{w_H}{w_C} - 0.2509\frac{w_O}{w_C}\left(1+0.7256\frac{w_H}{w_C}\right)+0.0383\frac{w_N}{w_C}\right]}{1-0.3035\frac{w_O}{w_C}}\ \text{for}\ 0.5\ \leq\ \frac{w_O}{w_C}\ \leq 2 \end{cases} \tag{20}$$

For the gasification reaction of the biomass the following reaction has been assumed:

$$x_1\ C_sH_mO_pN_qS_r + \ x_2\ O_2 + \ x_3\ H_2O \\ = \ x_4CO_2 + x_5CO + x_6H_2 + x_7CH_4 + x_8C(\text{char}) + x_9NO_2\ + x_{10}\ SO_2 \tag{21}$$

When x_1 and the molecular structure of the biomass are determined, several sub-equations can be derived from above equation to solve for the unknown variables:

$$\text{Carbon equation:}\ x_1 \times\ n = \ x_4 + \ x_5 + x_6 + x_7 \tag{22}$$

$$\text{Hydrogen equation:}\ x_1\ \times m + 2y_3 = \ 2x_6 + 4x_7 \tag{23}$$

$$\text{Oxygen equation:}\ x_1\ \times p + 2\ x_2 + x_3\ = \ 2x_4 + \ x_5 + 2x_9 + 2x_{10} \tag{24}$$

$$\text{Nitrogen equation:}\ x_1 \times q = \ x_9 \tag{25}$$

$$\text{Sulphur equation:}\ x_1 \times r\ = \ x_{10} \tag{26}$$

The product ratio of methane to hydrogen for small-scale fixed-bed co-current gasifiers at 1,200 K has been assumed to be [187]:

$$\text{Hydrogen to methane ratio:}\ x_6 = \ 9x_7 \tag{27}$$

A key parameter for the gasification process is the Equivalent Ratio (ER), which describes the ratio of actual air supply (and hence actual oxygen supply) over the stoichiometric air supply. For optimal gasification the equivalence ratio (ER) has been assumed to be 0.4, where the following product ratio of carbon dioxide to carbon monoxide is reached [188]:

$$CO_2\ \text{to CO ratio:}\ x_4 = \ x_5 \tag{28}$$

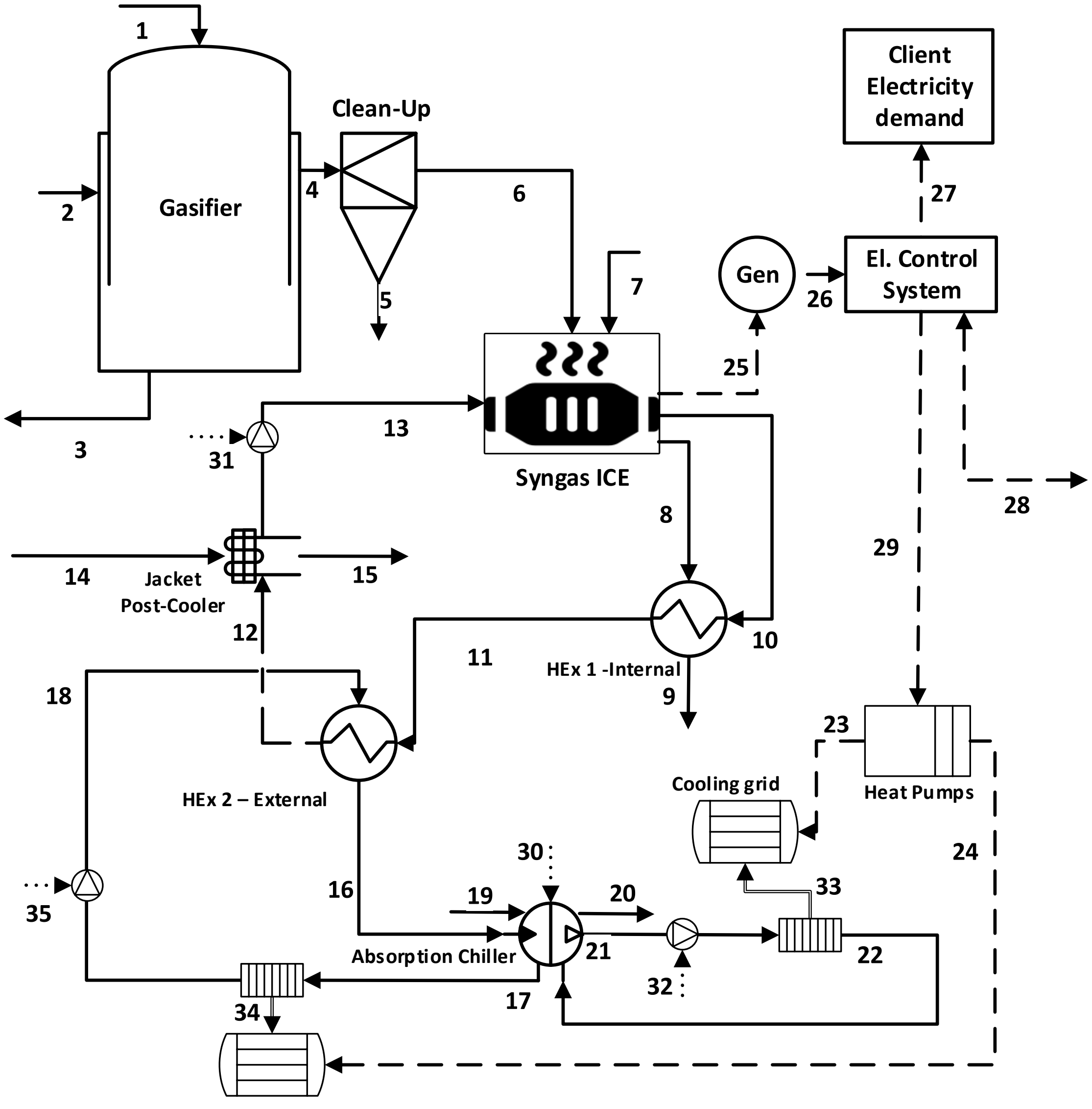
Based on equations (14) - (28) and the system layout, the exergy efficiencies for each component can be calculated as shown in Table 17.

Table 17 Efficiency calculations for key components

Component	Efficiency	Component	Efficiency
Gasifier	$\frac{\dot{e}_{4}}{\dot{e}_{1}}$	ABS	$\frac{-(\dot{e}_{21} - \dot{e}_{22})}{\dot{W}_{30} + \dot{e}_{17} - \dot{e}_{16}}$
Filter	$\frac{\dot{e}_{6}}{\dot{e}_{4}}$	Cooling Stream (CCHP)	$\frac{\dot{e}_{33}}{-(\dot{e}_{21} - \dot{e}_{22})}$
Engine	$\frac{\dot{W}_{25} + \dot{e}_{8} + (\dot{e}_{10} - \dot{e}_{13})}{\dot{e}_{6}}$	Heating Stream (CCHP)	$\frac{\dot{e}_{34}}{-(\dot{e}_{21} - \dot{e}_{22})}$
HEx1	$\frac{\dot{e}_{11} - \dot{e}_{10}}{\dot{e}_{8}}$	Aux. Cooling* (HP)	$\frac{\dot{e}_{23}}{\dot{e}_{29,1}}$
HEx2	$\frac{\dot{e}_{16} - \dot{e}_{18}}{\dot{e}_{12} - \dot{e}_{11}}$	Aux. Heating* (HP)	$\frac{\dot{e}_{24}}{\dot{e}_{29,2}}$
Total CCHP*	$\frac{\dot{W}_{25} - \dot{W}_{system} + \dot{e}_{33} + \dot{e}_{34}}{\dot{e}_{1}}$	Total HP	$\frac{\dot{e}_{24} + \dot{e}_{23}}{\dot{e}_{29}}$

*with $\dot{W}_{system} = \dot{W}_{30} + \dot{W}_{31} + \dot{W}_{32} + \dot{W}_{35}$

Icons designed by Skyclick and Freepik from www.flaticon.com



1: $m_{biomass}$
2: $m_{gasifier,air}$
3: $m_{gasifier,char}$
4: $m_{gasifier,syngas}$
5: $m_{clean\text{-}up,ash}$
6: $m_{clean\text{-}up,syngas}$
7: $m_{air,intake}$
8: $m_{eng,exhaust,hot}$
9: $m_{HEx2,exhaust,cool}$
10: $m_{JW,afterEngine}$

11: $m_{JW,afterHEx1}$
12: $m_{JW,afterHEx2}$
13: $m_{JW,afterCooler}$
14: $m_{afterCooler,in}$
15: $m_{afterCooler,out}$
16: $m_{HotWater,afterHEx2}$
17: $m_{HotWater,afterABS}$
18: $m_{HotWater,afterClient}$
19: $m_{ABS,CoolingW,in}$
20: $m_{ABS,CoolingW,out}$

21: $m_{chilledW,supply}$
22: $m_{chilledW,return}$
23: $Q_{HP,cooling}$
24: $Q_{HP,heating}$
25: $E_{eng,kinetic}$
26: $E_{gen,elec}$
27: $E_{el\_control,endclient}$
28: $E_{el,\ grid}$
29: $E_{el\_control,HP}$
30: $E_{el,\ AbsChill}$

31: $E_{el,\ Pump\_engine}$
32: $E_{el,Pump\_coolWater}$
33: $Q_{cooling,endclient}$
34: $Q_{heating,endclient}$
35: $E_{el,\ Pump\_hotWater}$

Figure 34 CCHP/HP system layout

4.4.2. Main findings

For a CCHP/HP system with a 25 kW_e engine the exergy efficiencies of the gasifier and the clean-up are not affected by load changes or ambient temperatures and are 78% and 83%, respectively. These can be considered typical values for wood-based gasification [189]. The engine exergy efficiency fluctuates most of the time between 80% and 95% depending heavily on the jacket water cooling temperature before engine entry and the partial load. HEx1 transfers heat from the exhaust gas to the jacket water with an exergy efficiency of 50%-60% during most operations hours. When HEx2 transfers heat from the hot jacket water loop to the hot water loop of the ABS, the exergy efficiency is most of the time at around 93%.

The exergy efficiencies of the absorption chiller, the heat streams to the consumer, and the heat pumps of a CCHP/HP system with a 25 kW_e engine are shown in Figure 35 and Figure 36. Interestingly, the exergy efficiency of the ABS varies the most and reaches peak values of up to 95%. This can be attributed to the many input parameters (e.g. chilled water temperature and mass flow, hot water temperature and mass flow, partial load, etc.). However, a clear trend line indicating higher efficiencies in winter than in summer can be observed. The exergy efficiencies of the final heat streams provided by the CCHP system are relatively stable with the efficiency for heating and cooling hovering around 17% and 86%, respectively. The big difference between the two values can be explained with the relatively larger temperature difference between heat stream supply and ambient temperature. For the HP, the exergy efficiency in heating mode ranges most of the operation times between 35% - 38%. It can also be observed that even for the small CCHP system, HP heating is only needed for some winter days, but not at all in summer. In cooling mode, the HP exergy efficiency fluctuates between 15% - 23% most of the operation times.

A comparison of the CCHP and the HP sub-system exergy efficiencies is shown in Figure 37. The HP sub-system efficiency drops significantly from 40.5% for the only-HP case to 25.4% for the smallest CCHP sub-system case. However, the smallest CCHP sub-system has the highest exergy efficiency of the CCHP sub-systems with 13.3% and with a continuing downwards trend for larger CCHP sub-systems. This can be explained by the decreased utilization of recovered heat as well as the decreased efficiencies when operating more often under lower partial loads. These exergy values are in range of the results found by other studies for similarly mild climates [190,191].

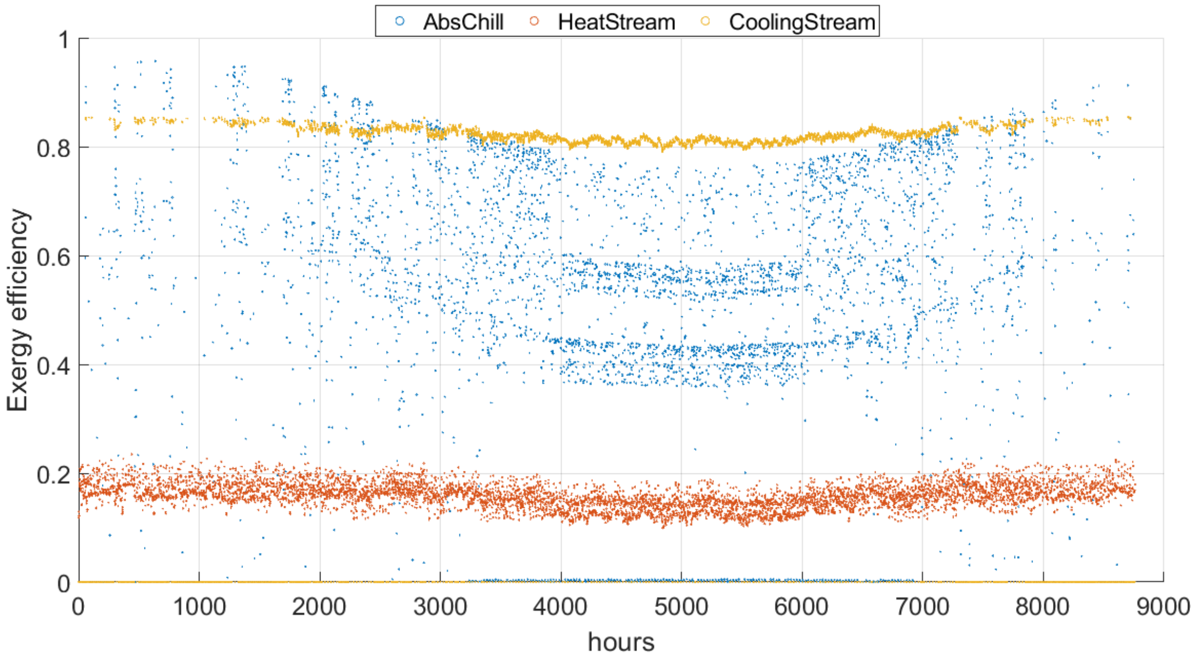


Figure 35 Exergy efficiencies of the ABS and both heat streams (from the CCHP) for a 25 kW$_e$ CCHP system

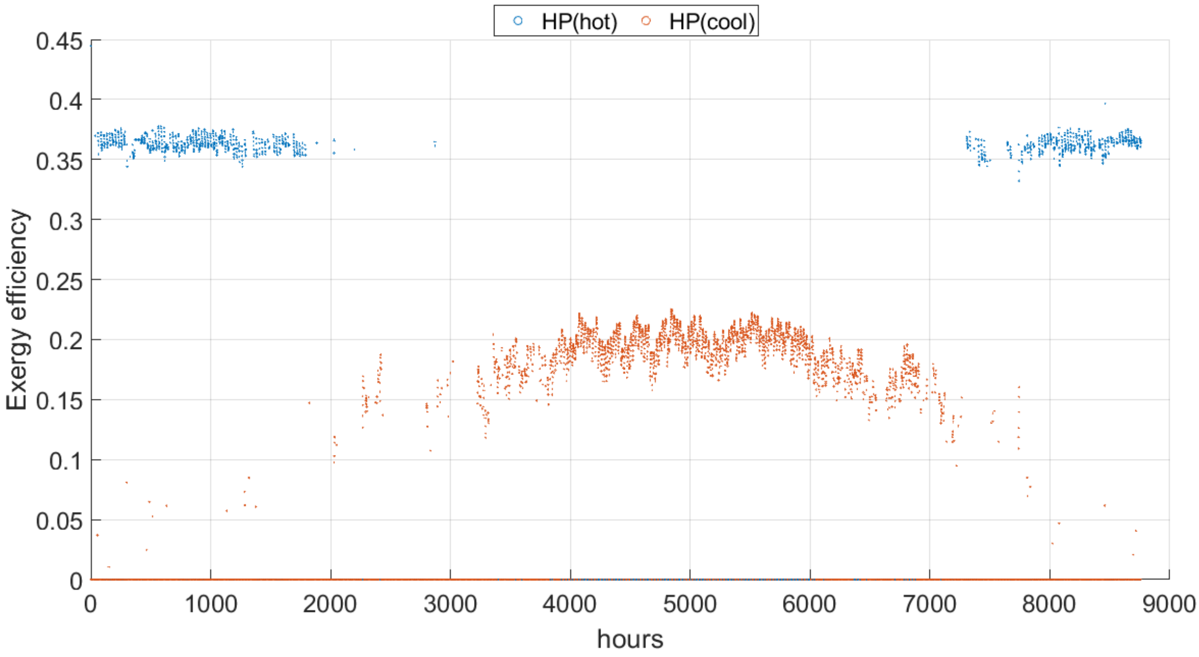


Figure 36 Exergy efficiencies of the HP for a 25 kW$_e$ CCHP system

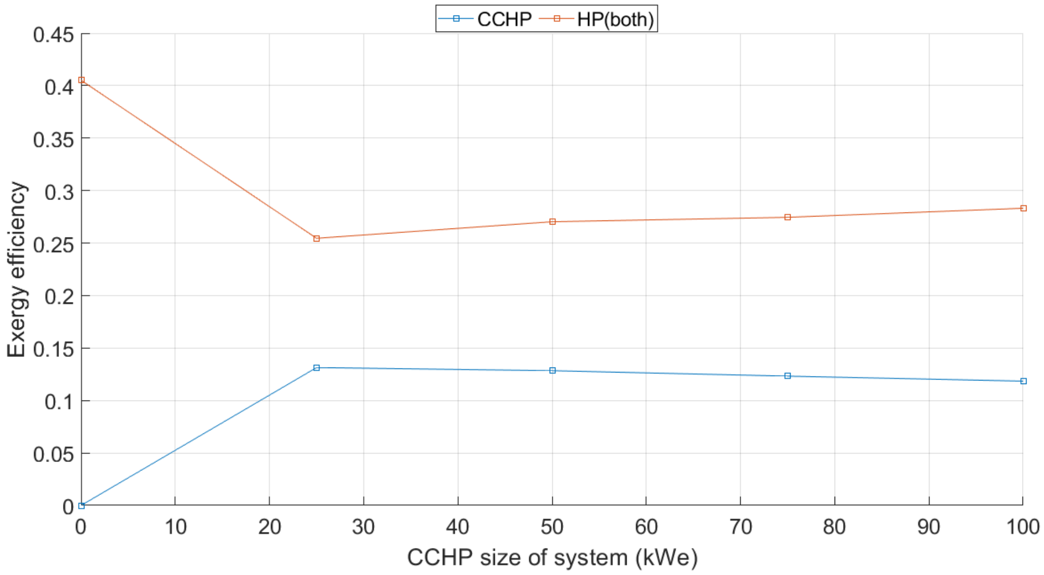


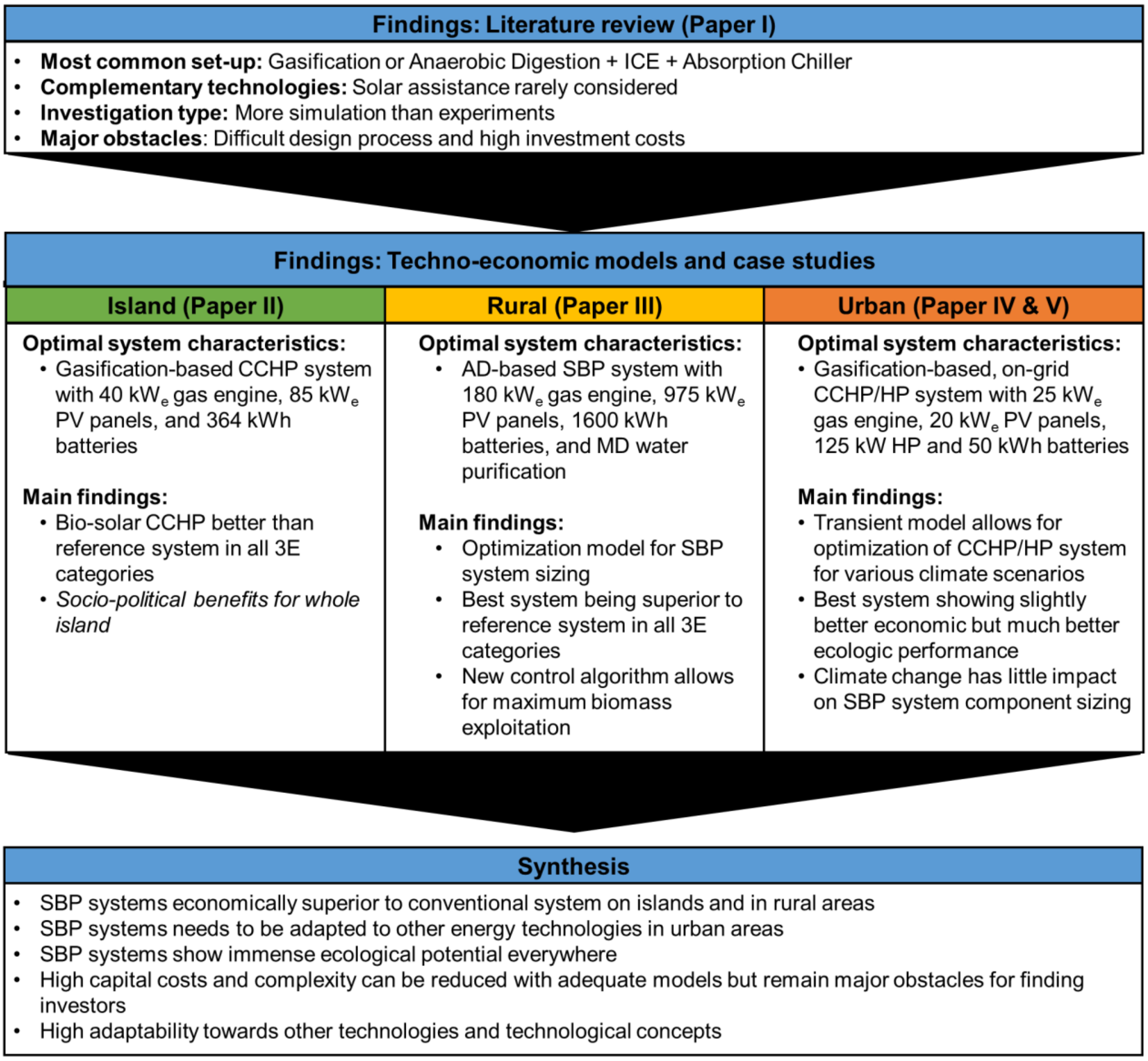
Figure 37 CCHP and HP subsystem exergy efficiencies for various sizes

4.4.3. Concluding remarks

By using an exergy analysis, the study focused on the technical aspects of the proposed CCHP/HP system and revealed that by adding a CCHP system to support a HP system exergy efficiency drops will occur for the latter. The study also underlines the comparatively high efficiencies of small CCHP systems, while larger systems only worsen the exergetic performance. Combining the model of this study with the modelling approach as well as the model of the study of Chapter 4.3, a thorough techno-economic analysis can be conducted for any given CCHP/HP system in any given location.

5. Synthesis and discussion

For a broader and more encompassing analysis, not just the individual studies are analysed but also a synthesis of their results is conducted. This meta-analysis will help to respond to the main research questions raised in Chapter 1.1 and specifically to the questions of when and where SBP systems are feasible options. It must be noted once more that the case model publications only indicate trends but should not be considered as definitive scientific proof due to their small sample size. An overview of the compiled findings of each paper within the structure of the thesis and a synthesis of these findings is shown in Figure 38.



Findings: Literature review (Paper I)

- **Most common set-up:** Gasification or Anaerobic Digestion + ICE + Absorption Chiller
- **Complementary technologies:** Solar assistance rarely considered
- **Investigation type:** More simulation than experiments
- **Major obstacles**: Difficult design process and high investment costs

Findings: Techno-economic models and case studies

Island (Paper II)

Optimal system characteristics:
- Gasification-based CCHP system with 40 kW_e gas engine, 85 kW_e PV panels, and 364 kWh batteries

Main findings:
- Bio-solar CCHP better than reference system in all 3E categories
- *Socio-political benefits for whole island*

Rural (Paper III)

Optimal system characteristics:
- AD-based SBP system with 180 kW_e gas engine, 975 kW_e PV panels, 1600 kWh batteries, and MD water purification

Main findings:
- Optimization model for SBP system sizing
- Best system being superior to reference system in all 3E categories
- New control algorithm allows for maximum biomass exploitation

Urban (Paper IV & V)

Optimal system characteristics:
- Gasification-based, on-grid CCHP/HP system with 25 kW_e gas engine, 20 kW_e PV panels, 125 kW HP and 50 kWh batteries

Main findings:
- Transient model allows for optimization of CCHP/HP system for various climate scenarios
- Best system showing slightly better economic but much better ecologic performance
- Climate change has little impact on SBP system component sizing

Synthesis

- SBP systems economically superior to conventional system on islands and in rural areas
- SBP systems needs to be adapted to other energy technologies in urban areas
- SBP systems show immense ecological potential everywhere
- High capital costs and complexity can be reduced with adequate models but remain major obstacles for finding investors
- High adaptability towards other technologies and technological concepts

Figure 38 Summary of main findings and synthesis of results

While for the island and the rural case the economic performances of the proposed SBP systems clearly outperform the reference case systems, the results are more ambiguous for the urban case study. With increasing CCHP size and hence with increasing energy autonomy, the NPC drops steadily indicating that an autonomous only-CCHP system would not be able to economically compete with an only-HP system. Hence, the economic superiority of CCHP-systems in urban areas is not as apparent as in more isolated areas. This indicates that from a socio-geographical perspective SBP systems are especially interesting in isolated areas with no or at least an unstable grid connection, which are most often found in developing countries.

Although SBP systems can play an important role in urban systems, they will have to compete with other biomass conversion technologies over limited biomass resources. Especially with the transport sector lagging behind in its transformation towards more sustainability, biomass-derived fuels (e.g. biodiesel, methane, hydrogen) may become the prevalent purpose of biomass conversion. The commercial future of SBP systems will therefore be likely concentrated in rural and developing areas as a transitionary technology until more alternatives become available, while in developed areas larger biomass polygeneration systems will be employed with a greater focus on biofuel generation.

This thesis focused on the techno-economical perspective of a SBP system designer and/or operator. An analysis of the impact of SBP system from a more socio-political standpoint could reveal more policy tools to be considered for supporting the use of SBP systems. In this context, the future economic development of the studied case locations independent from the SBP system has been neglected. However, especially in developing countries a rise in population as well as in electricity demand can be expected. Future models should therefore take these factors into account for optimal system sizing.

Another key factor for the economic performance of the systems is the discount interest rate. In the presented studies a fixed value as stated by government or commercial sources has been used. While in some uncertainty analyses the capital costs of machinery and the fuel costs were analysed, varying discount rate values could reveal very different results. As primary objective parameter, the NPC cost function was chosen albeit for most energy systems the more common LCOE parameter is the preferred choice. Due to the production of not only electricity but also other services like potable water, the LCOE parameters seems less suitable for SBP system analyses. However, other economic parameters like payback time or technical parameters like primary energy savings could be considered in future studies depending on the study objectives.

Especially for economic values, local policies can have great impact on the system's economic performance. Not just the input value, but also the choice of the simulation tools should remain open for discussion. Although arguments for the choice have been put forward in Chapter 2 as well as in each presented paper, many alternatives remain to be considered. Therefore, many alternative ways to simulate SBP systems remain, whereas each simulation program may have its own specific advantages. The presented studies focused also primarily on the use of PV panels as primary solar technology, but neglected the possibilities offered by solar-thermal technologies. These solar-thermal technologies could be applied in many ways as shown in Paper I and could improve SBP system efficiencies in many ways as well. However, in all studies the primary energy service to be served was electricity, where PV panels do contribute more directly to this objective than solar-thermal technologies.

Considering the first major obstacle as identified in Paper I, the results of the case studies have shown that the long-term benefits outweigh the short-term costs. The models can be used to lower the investment costs to a certain degree. Nevertheless, smart business plans will be necessary to overcome the still high capital cost obstacles. As shown in the case studies, governmental entities can benefit from SBP systems with increased grid resilience, greater energy autonomy, and the creation of local trade networks based on residual products from the biomass conversion process. Hence, these entities may be interested in subsidising SBP systems for long-term stability of their corresponding administrative area.

In relation to the second major obstacle, the complexity of the proposed systems could only marginally be addressed. While the HOMER-based studies of Papers II and III can be conveniently adapted to other case studies by other engineers, the more advanced TRNSYS models would certainly increase the complexity of the SBP design process. The complexity and consequentially the increased skill requirements of controllers for operating and maintaining the system can be burdensome for isolated areas, where access to a flexible workforce is comparatively lower. Therefore, any SBP system proposal should include a reasonable training plan for local technicians and engineers. On the one hand, this can be seen as an additional investment obstacle but on the other hand this can be regarded as an argument for subsidies due to the opportunity of creating local employment. One future task could be simplifying the use of the proposed models with a more user-friendly layout, so that other engineers can easily adapt the model input to their proper case studies [26]. Additionally, alternative software techniques (e.g. GIS-based software, machine learning) could be used to modify the models and expand their application use, for example to find ideal placement sites.

All case studies have shown much better environmental performance than the reference systems including the comparatively energy efficient only-HP system of Paper IV. However, in order to create a more sustainable environment for any given SBP system, the biomass resources have to be studied carefully. The importance of biomass supply only from sustainably managed and optimally local sources cannot be overstated in this context. While plant-based biomass will likely be able to regrow within a given timeframe in order to reabsorb any carbon products, animal-based biomass may not reach the same level of carbon recapturing and long-term sustainability. In all cases, nutrient elements (e.g. phosphor, nitrogen) should not be discarded after the biomass conversion process but instead should be redistributed to its origin. An approach on how to create such a nutrient cycle has been indicated in Paper III but more in-depth analyses have been carried out by other scientists [192].

Although in the review in Chapter 1 and in the presented studies many advantages have been demonstrated for the use of biomass, the entire topic remains controversial within science, politics, and industry. Even with second generation biofuels, the competition for “land, water, labour, and capital” with food production and natural conservation habitats continues [193]. Especially for woody biomass, many hopes have been put on gasification applications since the 1980s, but they do not seem to have materialized into a commercial breakthrough [194]. Instead, for the short-term small-scale gasification will most likely remain a particular solution for a niche market, where large shares of the market are increasingly absorbed by simpler PV-battery solutions.

Paper III and Paper IV can be considered as examples for the flexibility of the SBP concept in combination with other technologies. All studies show that the presumably competing solar and battery technologies can actually enhance (or be enhanced with) the polygeneration concept. While in the rural case study of Paper III the storage technologies have been put into focus, the adaptability towards other energy efficient technologies in the form of HP has been demonstrated in the urban case study of Paper IV. This flexibility towards complementing technologies brings both advantages and disadvantages; while it allows for more flexible energy system designs, it also leads to even more complex systems. It can therefore be argued that the proposed models including additional supportive technologies present a sort of trade-off, where capital costs may be lowered but the complexities not only of the system but also of its conception process are increased.

Due to the increasingly rapid development of technologies within the area of RES and storage solutions but also within the field of modelling, any predictions for the mid- to long-term future of SBP systems are subject to many uncertainties. Even for short-term planning, many uncertain factors can influence the development of SBP systems. For example, regional events like a change of political governance can reduce or increase state subsidies for such systems. Or natural disasters, which are deemed to occur more frequently and less predictably due to climate change, can alter the availability of certain types of biomass. Any future SBP system development proposal should therefore contain reasonable contingency plans.

6. Conclusions

6.1. Summary

Optimizing the efficient use of renewable energy resources and providing a variety of energy services with highly flexible energy systems will be crucial for a successful 21st century energy transition. Following this goal, the thesis studies the potential of biomass-based polygeneration systems and presents the state of the art on highly efficient SBP systems and technologies. Subsequently, various innovative systems and models are developed, which indicate the great energetic, environmental, and economic (3E) potential of SBP systems, but do also underline their inherent drawbacks.

In order to answer the research questions, the thesis starts with a thorough literature review on the state of the art of SBP systems giving an overview of the most common SBP technologies and system configurations. Suitable 3E parameters are identified, which allow for techno-economic analyses of SBP systems and comparing these to chosen reference systems based on more conventional energy generation methods. The literature study reveals that several researchers have attributed enormous 3E potential to SBP systems, especially in combination with solar technologies, but it also indicates that high investment costs and high complexity of the systems present obstacles for further deployment of SBP systems in the field. Based on the literature study, various SBP systems and models have been conceived for various socio-geographic locations and with distinct research focuses.

Firstly, a gasification-based, solar-assisted CCHP system for a small holiday resort on an isolated, tropical island setting has been designed and compared to a reference diesel-based system. The proposed SBP system has been investigated for its techno-economic potential for the system owner as well as for its socio-economic potential for the entire island community. The results indicate that the SBP system has enormous economic savings and GHG emissions reduction potentials, but could also benefit local farmers and grid operators on the island. The proposed model optimizes for project lifetime cost reduction, but the capital costs still remain obstructively high.

Secondly, an anaeraobic digestion-based, PV-assisted SBP system for electricity and potable water generation has been designed featuring two different energy storage technologies: biogas storage and batteries. To maximize the electricity generation from the available biomass, a control algorithm has been programmed, which determines when and how to use the biogas engine and the batteries depending amongst others on the consumer load and the PV power generation. Employing the proposed SBP system model in a case study for a rural locality in a tropical area, it could be demonstrated that the system would lead to cost reductions of more than 22% over its project lifetime coupled with enormous CO_2 emission reductions of 98% compared to a fossil fuel based reference system. However, significant additional PV power capacity would be required to satisfy the energy localities' energy demands pushing the overall capital costs of the system to nearly 8000% of the reference system's capital costs. The developed model shows that biomass storage is compatible with other storage solutions and that using water purification technologies can make SBP systems viable alternatives even in mild temperature zones.

Thirdly, two different models for a gasification-based SBP system collaborating with HPs have been presented with the first focusing on a techno-economic analysis and the second on an exergetic analysis of the system components as well as of the entire system. The novelty of the first model lays not just in the SBP system design but also in including the effects of future climate change on SBP system performance in the model. The second model focuses on the changes in exergy efficiency of all components depending amongst others on different seasons and component sizes. Applying both models in a case study for an urban tourist facility in a mild climate zone, it could be shown once more that enormous GHG savings potential exists compared to an electricity-based, grid-connected solution, but only minor economic savings could be achieved. Operating a larger system in island-mode seems not economically feasible as a smaller SBP system with grid-connection has been determined as economically best option. This correlates with lower exergy efficiencies for larger systems. Climate change seems to have only a marginal impact on system performance and hence on system design.

The synthesis of the results responds directly to the main research questions on where SBP systems are feasible alternatives to conventional reference systems and what are their 3E benefits and drawbacks. SBP systems are especially attractive in more isolated environments more often found in rural areas or on islands. While the models proposed in this study can lower the capital investment costs, system complexity remains a crippling attribute, which is especially burdensome in areas with little access to skilled technicians and engineers. Operating SBP systems in island mode in urban settings seems not to be economically sensible due to easier access to larger electric grids and alternative technologies. Instead, intelligent control mechanisms of SBP systems as integrated parts of larger networks are required.

The studies presented in this thesis support the existing body of knowledge on SBP systems by presenting novel SBP system designs and modelling approaches for a variety of applications. Hence, the proposed models facilitate the design of future SBP systems. The models also underline the general adaptability of the SBP concept towards solar-battery solutions as well as other energy efficient technologies. The specific thesis contributions to the state of the art can be summarized as follows:

1. A thorough and structured review of available literature on SBP systems, specifically on CCHP systems, has been presented.
2. A study taking into account not just the techno-economic but also the socio-political impacts of an innovative SBP system for an entire island community has been performed.
3. To address the gap in literature on the combination of SBP systems with various storage devices, an original modelling approach was presented with a new control algorithm employed in a model for SBP systems suitable for electricity and water provision.
4. Finally, it was investigated how SBP systems can be optimally sized for cooperation with HPs while also considering the impacts of climate change on the system performance. For this, a new modelling approach has been presented and tested with two new models in a case study.

6.2.Future investigations

The increased interest in solutions related to the 21st century energy transition have also increased the interest in SBP systems, both academically and commercially. As shown in this thesis, the SBP concept can be adapted to other RES, specifically to solar technologies. Future research will therefore have to increasingly address the inherent advantages of biomass-based solutions over other RES but also how SBP systems can enhance (or can be enhanced by) other RES technologies. Likewise, the storage aspect of biomass can be complemented by other energy storage technologies; not only batteries but also storage technologies like flywheels or hydro-pump stations could be considered for investigation.

Not just competing or complementing technologies, but also those easily incorporable within the SBP system will develop further in the coming years. Great hopes are placed on micro turbines and ORC for the near future. Research on Stirling engines could lead to successful solutions for direct combustion of biomass too. For thermal cooling technologies, although absorption-based solutions seem to dominate the market, both desiccant wheels and adsorption chillers may find their niche markets, for example for dehumidification or for very low maintenance applications, respectively. Further development in thermally-driven water purification technologies like MD might also create new opportunities for the SBP concept. Great hopes are also placed on bio-char generation from gasifiers, which then can be transformed to other types of bio-fuels and hence increase the services provided by a SBP system using gasification.

Apart from the machinery, the software used to design SBP systems will certainly improve further. Although a brute-force approach seems to be a feasible solution for smaller polygeneration systems due to the relatively small search space, other optimization techniques like GA or EA could speed up the computation process. This may be especially useful when choosing various output parameters for optimization instead of just the project lifetime costs. Future investigations will have to consider the effects of varying interest rates on the model and will have to take into account the implications of rising populations and rising demands, which will be especially important in economically developing areas. Although proposed models for SBP systems show increasingly better 3E performances in scientific studies, these systems tend to become more complicated, which may be a reason why some investors are appalled from investing into such systems. Eventually, each model creator will have to find a suitable compromise between modelling detail and computational requirements but also between complexity and comprehensibility.

The trends presented in Chapter 5 are only indicating the suitability of SBP systems for various socio-geographical locations. Future investigations could solidify or disprove the statement by analysing greater numbers of case studies. Similarly, investigations on how changing weather patterns could affect polygeneration systems placed in regions that are more affected by climate change than the Mediterranean basin may provide other results than those presented in this thesis.

Naturally, by escaping the limitations set for this thesis many other investigation routes can be taken. Hybrid solutions using both biomass and fossil fuels can be considered as a transitionary solutions for SBP systems allowing for more flexibility. Although this thesis concentrates on SBP systems working in island-mode, which are especially interesting in isolated areas, grid-connected systems for urban areas exhibit many promising features too. Future investigations will focus on how to control distributed renewable energy systems to provide energy autonomy while being parts of a a superior network.

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Annex I

Links to model code

All data and code used for developing the HESS polygeneration system of Paper III can be found here: [DOI: https://zenodo.org/record/4048090](https://zenodo.org/record/4048090)

Building data for the Montjuic castle

Table 18 Area description, size, and occupation profile

Area Name & Acronym	Floor Area (m^2)	Activity Profile
Residence (R)	699.48	Residence
Administration and Services (C2)	614	Administration
Administration and Services (C3)	99.19	Administration
Kitchen and Bar/Restaurant (C4C5)	337.69	Restaurant
Shop (C6)	326.02	Exposition/Shop
Service, Administration and Group Rooms (P3P4P5)	655.20	Exposition/Shop
Room for Large Groups (P6)	326.02	Exposition/Shop
Documentation Centre (C8P8)	319.13	Administration
Restrooms (C9)	367.84	Services
Entrances (E1E2)	269.10	Passage ways

Table 19 Area description with occupation, illumination and ventilation characteristics

Area Name & Acronym	**Floor Area**	**Occupation Profile**	**Illumination Potential**		**Ventilation**	
	m^2		**W/m^2**	**kW**	**Mflow ext (m^3/h)**	**Renov. (1/h)**
Residence (R)	699.48	Residence	17	12.00	2124	1.00
Administration and Services (C2)	614	Administration	13	7.99	2764	1.5
Administration and Services (C3)	99.19	Administration	13	4.39	1520	1.5
Kitchen and Bar/Restaurant (C4C5)	337.69	Restaurant	13	1.29	446	1.5
Shop (C6)	326.02	Exposition/Shop	13	4.37	1512	1.5
Service, Administration and Group Rooms (P3P4P5)	655.20	Exposition/Shop	13	8.52	2948	1.5
Room for Large Groups (P6)	326.02	Exposition/Shop	13	4.15	1436	1.5
Documentation Centre (C8P8)	319.13	Administration	13	4.24	1467	1.5
Restrooms (C9)	367.84	Services	13	4.78	1104	1.00
Entrances (E1E2)	269.10	- (Passage ways)	13	3.50	-	-

Table 20 Area profiles

Areas	**Occupation Profile**	**Temperature Profile**	**Humidity Profile**	**Activity Profile**	**Electric devices**	**Hot Water profile*** [195]
Residence	Mo-So 00.00-24.00	21-25 ºC	40-60 %	Seated, light work (150 W p.p.)	Electric terminals (80 W p.p.)	30 l/client/day
Administration	Mo-Fr 09.00-18.00	21-25 ºC	40-60 %	Seated, light work (150 W p.p.)	Electric terminals (80 W p.p.)	5 l/employeeday
Restaurant	Mo-Sa 10.00-23.00	21-25 ºC	40-60 %	Seated eating (170W p.p.)	Electric terminals (80 W p.p.)	10 l/cost./day
Exposition/ Shop	Mo-So 10.00-22.00	21-25 ºC	40-60 %	Standing, light work, walking slowly (185W p.p.)	Electric terminals (80 W p.p.)	5 l/cost./day
Services	Mo-So 08.00-22.00	18-27 ºC	40-60 %	Seated, light work (150 W p.p.)	-	5 l/cost./day

*With minimum HTW temperature = 60 ºC

Table 21 Construction element characteristics

Construction Element	**Building material**	**U-Value (W/m^{2}K)**	**Avg. Thickness (m)**
Int. Wall (Patio)	Stone	2.094	0.95
Ext Wall (Patio)	Stone	1.741	1.25
Ground floor (Patio)	Stone	2.141	0.7
Roof (Patio)	Stone, Sand, Gravel	2.094	0.95
Adj. Ceiling (Residence)	Stone, concrete beams, ceramic joining	1.549	0.24
Ext Wall (Residence)	Brick, Mortar, Cement	0.541	0.5
Ground floor (Residence)	Concrete	2.296	0.3
Ext. Roof - Pyramidal (Residence)	Arabic tiles, concrete beams, ceramic joining	1.519	0.24
Windows	Aluminium frame, double-glazed	3.000	0.24

Annex II

Published Paper

Non-open access publications:

Paper I:

doi:10.1016/j.rser.2018.07.044.

Paper IV:

doi:10.1016/j.enconman.2020.113256.

Open-access publications: