Chair of Energy Network Technology

Doctoral Thesis

Exergy Efficient Municipal Multi Energy Systems

Dipl.-Ing. Lukas Kriechbaum

October 2020

MONTANUNIVERSITÄT LEOBEN
www.unileoben.ac.at

EIDESSTATTLICHE ERKLÄRUNG

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

Datum 14.10.2020

Lukas Kriechbaum

Signature Author
Lukas, Kriechbaum

All natural and technological processes

Proceed in such a way that the availability

Of the remaining energy decreases

In all energy exchanges, if no energy

Enters or leaves an isolated system

The entropy of that system increases

Energy continuously flows from being

Concentrated to becoming dispersed

Spread out, wasted and useless

New energy cannot be created and high grade

Energy is being destroyed

An economy based on endless growth is

Unsustainable

Unsu

Unsustain unsustain unser

Uns' uns' unsustainer unsustainer

Unsu

Unsustain

Unsustain

Uns' uns' you're unsustainable

The fundamental laws of thermodynamics will

Place fixed limits on technological innovation

And human advancement

In an isolated system, the entropy

Can only increase

A species set on endless growth is

Unsustainable

Unsu

Unsustain unsustain unser

Uns' uns' unsustainer unsustainer

Unsu

Unsustain

Unsustain

Uns' uns' you're unsustainable

Matthew James Bellamy, The 2nd Law: Unsustainable

ABSTRACT

Mitigation of global warming is one of the greatest challenges society is facing in the 21st century. As a consequence, different global initiatives to decarbonise the energy system have emerged and have led to major technological innovation and integration of renewable energy sources (RES) into the energy systems. This, as well as increasing energy efficiency, has been identified in the literature as the most promising options for a sustainable energy system. Both are major challenges for current energy systems and their future planning and operation. Modelling can support the necessary transformation process by providing insights into the complex relationships of possible future energy systems with high shares of renewable energy sources.

This Ph.D. thesis deals with the modelling of exergy-efficient multi-energy systems (MES). In MES, various energy sources and sectors are linked by appropriate coupling technologies. This holistic approach allows cross-sectoral synergies to be exploited for implementing efficiency measures and the integration of renewable energy sources. In such a case, where different forms of energy are considered in one model, exergy is a good criterion for assessing resource efficiency because it also considers the second law efficiency.

In a first step a comprehensive literature review on the state of the research and the fundamentals of exergetic optimisation of MES is carried out. Based on the results, the requirements for a model for exergy optimisation are defined. The cumulative exergy consumption (CExC) concept fits them best. It considers all exergetic expenditures from the raw material to the final product or service. This means that both the exergy expenditures for energy import and the expenditures for installing the infrastructure are considered.

The existing CExC concept was adapted to create a methodology for exergy optimisation of municipal MES. It is applied to three different case studies. The open source modelling framework oemof is used for modelling. The results have shown that it is important to optimise design and operation of the energy system together as an exergy efficient operation is only possible if the design allows it. In addition, the modelling of the boundary conditions is of particular importance. In open systems, such as municipal MES, incorrectly chosen ones may lead to biased results. If the spatial resolution is modelled, different network coverages and limited line transfer capacities can be considered. Depending on the modelling method of the load flow equations, the results and computing times can differ significantly.

KURZFASSUNG

Die Eindämmung der globalen Erwärmung ist eine der größten Herausforderungen für die Gesellschaft im 21. Jahrhundert. Die daraus entstehenden globalen Initiativen zur Dekarbonisierung des Energiesystems führten zu einer großen technologischen Innovation und der Einbindung von erneuerbaren Energien in das Energiesystem. Dies sowie die Steigerung der Energieeffizienz werden in der Literatur als vielversprechendste Optionen für ein nachhaltiges Energiesystem genannt. Beides bedeutet für derzeitige Energiesysteme, als auch für deren zukünftige Planung und Betrieb, große Herausforderungen. Die Energiesystemmodellierung kann den erforderlichen Umwandlungsprozess unterstützen, indem sie Einblicke in die komplexen Beziehungen möglicher zukünftiger Energiesysteme mit hohem EE-Anteil gewährt.

Diese Dissertation beschäftigt sich mit der Modellierung von exergieeffizienten Multi-Energie-Systemen (MES). In MES werden die unterschiedlichen Energieträger und -sektoren durch geeignete Kopplungstechnologien miteinander verknüpft. Durch diese gesamtheitliche Betrachtung können sektorübergreifende Synergien bei den Effizienzmaßnahmen und der Einbindung der erneuerbaren Energien genutzt werden. In MES ist Exergie ein gutes Bewertungskriterium für die Ressourceneffizienz, weil sie neben dem ersten auch den zweiten Hauptsatz der Thermodynamik berücksichtigt.

In einem ersten Schritt wird eine umfassende Literaturstudie zum der Stand der Forschung sowie den Grundlagen zur exergetischen Optimierung von MES durchgeführt. Basierend auf den Ergebnissen werden die Anforderungen an ein Modell festgelegt. Die Methodik des kumulativen Exergieverbrauchs (CExC) deckt diese am besten ab. Der CExC berücksichtigt alle exergtischen Aufwendungen von der Primärressource bis zum fertigen Produkt oder Service. Das bedeutet, dass sowohl die exergetischen Aufwendungen für den Energieimport als auch die Aufwendungen für die Installation der Infrastruktur berücksichtigt werden.

Das bestehende CExC-Konzept wurde angepasst, um eine Methodik zur Exergieoptimierung von kommunalen MES zu schaffen. Sie wird auf drei verschiedene Fallstudien angewendet. Zur Modellierung wird das Open-Source-Modellierungsframework oemof verwendet. Die Ergebnisse haben gezeigt, dass es wichtig ist, Design und Betrieb des Energiesystems gemeinsam zu optimieren, da ein exergieeffizienter Betrieb nur möglich ist, wenn das Design dies zulässt. Daneben ist die Modellierung der Randbedingungen von besonderer Bedeutung. In offenen Systemen, wie es kommunale MES sind, können falsch gewählte Randbedingungen zu verzerrten Ergebnissen führen. Wird die räumliche Auflösung modelliert, können unterschiedlichen Netzabdeckungen sowie beschränkten Leitungstransferkapazitäten berücksichtigt werden. Je nach Modellierungsart der Lastflussgleichungen können sich die Ergebnisse und Rechenzeiten signifikant unterscheiden.

ACKNOWLEDGEMENTS

It was six years ago when I first walked into my new office at EVT. Table, chair, laptop, empty shelves, not much else. A lot has changed since then while I am now writing these lines shortly before submitting my thesis. Joining a newly found chair proofed to be an interesting challenge which is now coming to an end. It would have been a lot more strenuous and boring without the help of all the people that have influenced and supported me during this time.

Let's start with Thomas, supervisor of my PhD thesis. You offered me the position as PhD candidate only a few days after you yourself had become a professor there. Your attitude towards independent working gave me the freedom to develop and the opportunity to shape the chair and contribute to its scientific focus. The numerous PhD talks, the intense discussions on the commute, the successful proposals we wrote, your numerous attempts to explain me the physics behind electricity networks. However, for me as mechanical engineer electricity is still yellow and bites! Six years later I have to say thank you for all your support and the patience you had with me, especially with my publications in the last two years of my PhD.

Christoph, we shared the office for more than three years. I can't remember how many tons of chocolate, wine gums and cakes we ate during this time. That time was fun and I was lucky to have you there as my colleague. All the fruitful scientific discussions we had, the common train commutes, your support when I found myself stuck in a scientific problem, your help with my publications. In the end I am struggling to find the right word to express my gratitude for your support, my thesis wouldn't be what it is without all your valuable contributions.

Kerstin, Benjamin, Julia. You were the PhD candidates joining after me when EVT still was a small chair in its start-up phase. Rebekka and Jasmin, best secretaries, you made my live at EVT so much easier. Andreas, thanks for all the bike rides, climbing, hiking and ski mountaineering tips. Elisabeth, best proofreader for my publications. Thank you for all your support. You had always an open ear for me when things got complicated. My time at EVT would have been different without you. Thank you to all my other colleagues Anna (you made the most awesome cakes), Johannes (cake officer), Bernd, Matthias, Maedeh, Thomas, Paul, David.

Phillip, you just showed up at the right time. Without your enthusiasm and your endurance for Python coding my OPF model would have never been completed in time. You did a phenomenal work for your thesis! Many thanks also go to all other students whose thesis I supervised and who contributed to this thesis: Gerhild (you had the hardest task, you started with oemof and exergy optimization), Alexander, Felix, David, Romeo. You were a great support.

Bernd, university of Leoben has the best university sports. You brought me back to mountain biking, now I have more bikes than ever before. Mountain biking, cross country skiing, ice skating, ski mountaineering, climbing. Thanks for all the exciting courses so many awesome moments. I hope there are many to come!

I would also like to acknowledge people outside work which were a great support during the time of my PhD and which I shared great moments with. Armin, Florian, Peter and Josef, bouldering in the "Garage" with you was awesome. Even if we sometimes just met for a chat there. You always were there when there were hard times with my PhD. Finally, I will be the last of us to receive a PhD, now we are complete. Daniel there will be a lot more time for ski mountaineering from now on. Cheng, thanks for all the remarkable vacations. You were always there when you were needed. Don't do a PhD. Anja, thank you for all the chats, the bike rides and all the chocolate.

My flatmates Harri, Simone and Berndl, it was good to have you there when coming home after a long day in the office. The drinks and barbeques we had on the balcony. Thanks for being there.

Micha, midnight has already passed and I'm still sitting there to work on my last lines of my manuscript. Lulea, Stockholm, Hamburg, Graz. There is so many places we met, so many activities we did together. You have taught me more about scientific practice than many others. You brought me back on track when I was in despair and work was not progressing as planned. In recent times I have had far too little time to meet you and your family. I hope this will soon be possible again despite COVID. Thanks for all!

Mum, Dad. Simon, Antonia. Thanks for all your support. Physical work at home was a welcome change to office work for me.

Doing this PhD and writing this thesis was probably the toughest challenge in my life so far. Being a prototype at a newly founded chair did not make this task easier. In the begin there were too many variables and too few fixed parameters. Too many possible ways to go showed up, which I did not know where they would end. There are so many obstacles I did not think they even exist. So many imponderables that cannot be estimated. However, with the support of you all I managed to overcome any challenge and to further develop myself. Thank you all!

CONTENTS

NOMENCLATURE

Abbreviation

AC	Alternating current
CExC	Cumulative Exergy Consumption
CHP	Combined heat and power
DC	Direct current
DSM	Demand side management
ETSAP	Energy Technology Systems Analysis Program
GDP	Gross domestic product
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
LP	Linear programming
MARKAL	MARket ALlocation
MES	Multi energy system
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
NF	Network flow
PF	Power flow
RES	Renewable energy source
TIMES	The Integrated MARKAL-EFOM System

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The climate crisis demands for major changes in today's energy systems. Since the beginning of the industrial age fossil fuel use has contributed 68 % to the world's anthropogenic greenhouse gas emissions [1]. These greenhouse gases are the main cause for the rise of global temperatures. To limit the global temperature increase below $2\ °C$ compared to levels before industrialisation, the parties to the United Nations Framework Convention on Climate Change agreed at COP 21 in Paris to reduce CO_2-emissions [2]. Individual countries as well as the EU have derived their climate neutrality goals from this UN agreement [3].

Fossil fuel use for energy production and industrial processes is the major contributor to global greenhouse gas emissions [4]. To achieve a transformation towards a sustainable energy supply, a shift from fossil fuel-based energy sources to renewable energy sources (RES) is necessary. This requires extensive changes in the current energy systems. Since most RES generate electricity directly (except for biomass and geothermal energy), a change towards processes and technologies fuelled by electricity is necessary [5]. Furthermore, as RES potentials are limited, efficient technologies must be used.

To tackle this challenge, integrated approaches across multiple energy carriers are discussed in literature [6]. Already in current energy systems, many different energy carriers and forms are used simultaneously, e.g. heat, electricity, and natural gas. However, to date their planning and operation is mainly carried out independently. Coupling the infrastructure of different energy carriers and energy sectors with appropriate technologies allows to exploit cross sectoral synergies to raise the overall system efficiency. Such integrated, holistic energy systems can be also called multi-energy-systems (MES) [7].

A general example of a sector coupled MES is presented in Figure 1. Electricity, natural gas, heat, hydrogen, biomass etc. sectors are coupled by technologies such as boilers, CHPs, electrolysers, heat pumps, methanators. To fully exploit the potentials such a MES provides, a coordinated operation of the coupling technologies is necessary. For example, they can provide the necessary flexibility options needed for the integration of variable RES. The slow dynamics of heat and gas grids can be used to absorb the short-term dynamics in the electricity network, thus coupling intraday and seasonal variations. This allows MES to relieve the strains on the energy transmission and distribution infrastructure [8]. Another factor is that the natural gas network already offers high storage capacities and therefore is also suited for seasonal energy storage. Due to these advantages MES can play a vital role in decarbonising the energy system.

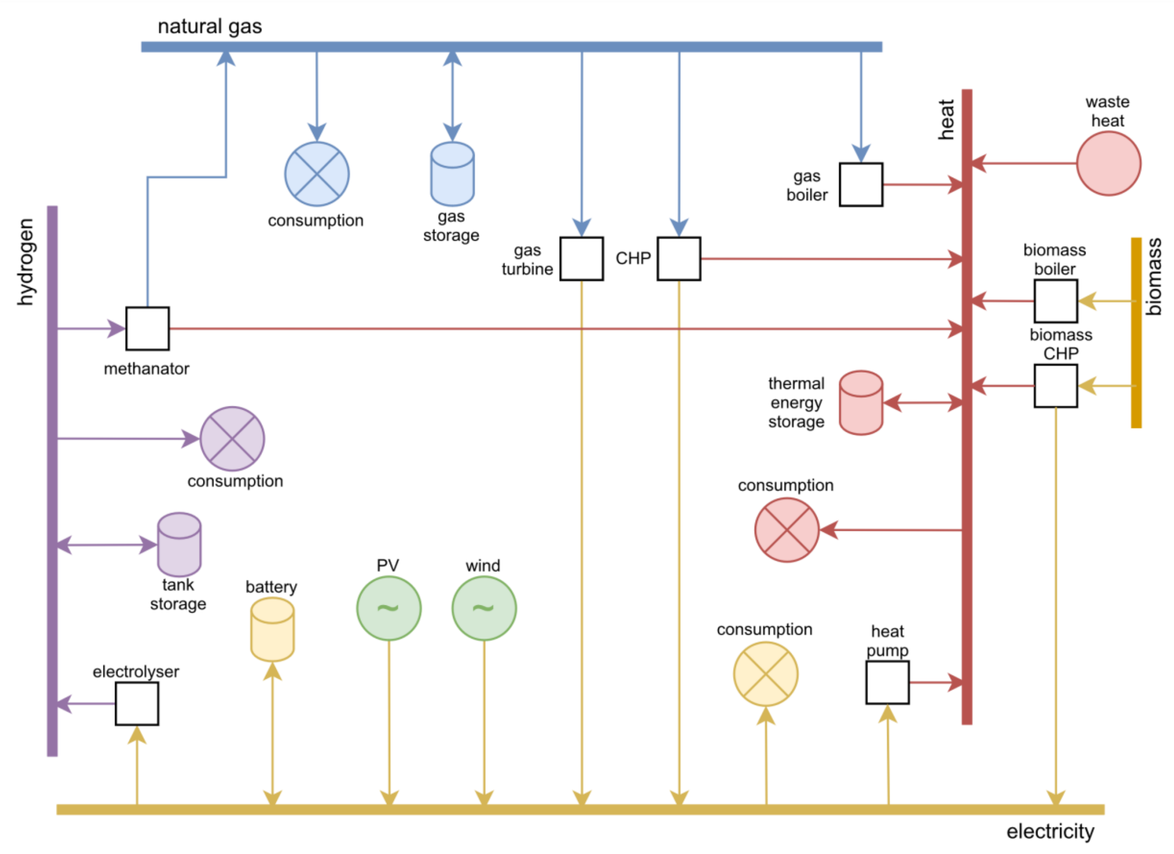

Figure 1: Sector coupling pathways and exemplary coupling technologies in a MES

However, the coupling of different energy carriers and sectors adds another layer of complexity. It makes planning and operation of such systems more demanding. For this challenge, modelling of MES can support and create the knowledge required for implementation. Recently, a wide variety of methods and tools have become available for this purpose [9]. However, also integrated MES models suffer from increased complexity. Despite increased computing power in the recent years, simplifications must be made to keep the models computationally tractable.

Besides the modelling itself, the analysis, interpretation, and evaluation of the results play an important role. While in the past the focus was on economic evaluation criteria, environmental criteria and resource efficiency have become more relevant performance indicators of an energy system in recent years. In the field of resource efficiency, the concept of exergy is a useful evaluation criterion. It describes the useful part of the energy, or also called the quality of an energy form. In addition, it accounts for the irreversibility of processes.

Currently, mainly highly exergetic energy carriers are used to cover the global energy demand. This results in large exergy losses, especially in the case of low temperature applications such as domestic heat for example. Therefore, the concept of exergy is very well suited to identify inefficiencies and propose other, more efficient options. It is also well suited as a common base in case of considering multiple energy carriers in one model [10]. By using an exergy approach in an MES it can be determined how efficiently the available exergy of the individual energy carriers is used and where losses occur. Together with suited models valuable contributions to the design and operation of future sustainable energy systems can be made. Because exergy and MES are such a fundamental concept, the developed methodology is universally applicable, from a single process to large energy systems of entire countries.

1.1 Thesis outline

This thesis builds on several papers that I have published in the course of my dissertation. All of them contribute to the content of this work with a different aspect. This thesis is structured as follows: Chapter 2 provides the state of the art of energy systems modelling, the global energy flows and renewable potentials and the fundamentals of exergy. The research objectives and the methodology are presented in Chapter 3. In addition, the contribution to scientific knowledge is stated and the contribution of the individual papers to this dissertation is presented.

Chapter 4 specifies the requirements for MES models, which are derived from the physical system. Building on those requrements, Chapter 5 presents a basic methodology for exergy optimisation in MES. This methodology is then applied using the example of a municipal energy system. Key findings from exergy optimisation and their interrelations are discussed in Chapter 6. An outlook is given in Chapter 7.

Three of the aforementioned peer-reviewed journal articles are presented in the Appendix A as the main part of this thesis. The appendix also includes a brief statement of the author’s contribution to each publication. This thesis concludes with Appendix B, which lists my papers in conference proceedings and the papers I co-authored with minor contributions.

2 MODELLING, ENERGY FLOWS & EXERGY

As decarbonisation is key and can be aided greatly by appropriate designed energy systems, this chapter starts with an introduction to energy systems modelling. This is followed by a discussion of the world's current energy sources, energy consumption, energy flows, energy utilisation, and RES potentials. The fundamentals of exergy conclude this chapter.

2.1 Energy Systems Modelling

What is the best way to tackle the issue of the energy system's decarbonisation? How to sustainably meet societies rising energy demands? This requires a comprehensive transformation of today's energy systems. Our current ones are the result of complex interactions of economy, society, environment, resources, and technology (Figure 2). Changes in one of the fields will inevitably affect all others as well. Models that take all four fields into account are called integrated assessment models. Besides that, there are many models that focus on sub-areas: power system models for the electricity supply, MES models for a holistic energy supply, economic models, etc.

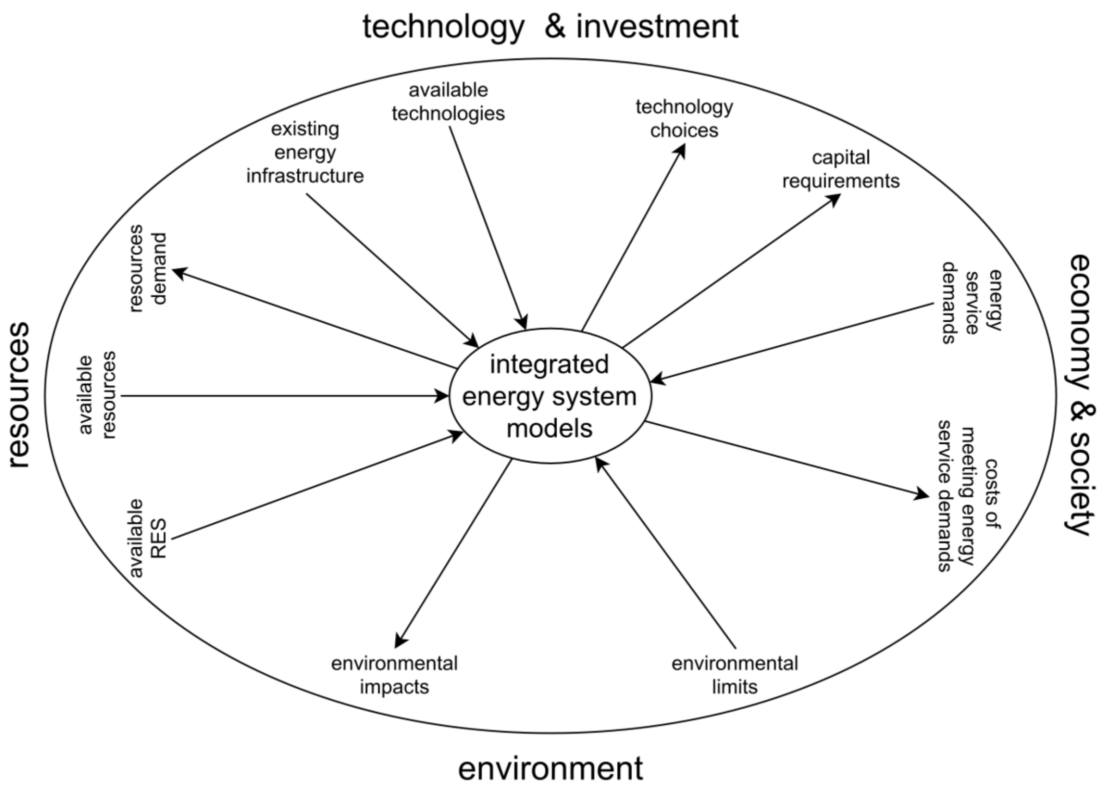

Figure 2: Fields of interaction in energy systems [11]

Energy systems modelling has been dealing with modelling those interactions since the 1970s. The oil crisis in 1973 triggered the development of the first models for the long-term evolution of energy systems [12–15]. Originally, they were developed for techno-economic bottom-up optimization of large-scale energy systems (e.g. on country level). Therefore, they require extreme simplifications, like aggregated values or annual supply and demand balances [16].

In the past, the main objective of energy system modelling was to create the energy policies to ensure a reliable and affordable energy supply. For this purpose, mainly technical and economic aspects were considered. However, the proceeding climate crisis has added sustainability to these objectives which requires an adaption of those policies. To enable an efficient transformation process, such models are needed to gain insight in the complex interrelations within an energy system [17].

This has also changed the requirements for energy system models. In the past, the energy systems were planned from top-down with central production units and grids for energy transmission and distribution. In addition, each energy carrier was considered separately, e.g. electricity, gas and heat grids were developed independently of each other [7]. Newer models must also consider the distributed characteristics of RES. The implementation is no longer centralized in a few places, but locally in the energy systems of cities and municipalities.

Most countries first concentrated on decarbonising their electricity sector. This sector consumes about 40% of the global primary energy demand and supplies 18% of the final energy demand [18]. More recently, the decarbonization of industry, heating and transport sectors has also come into focus. Synergies between the individual sectors can be exploited through an integrated approach in which all energy sources are considered together in a MES.

2.2 Global Energy Flows and RES-potentials

The main purpose of the global energy system is to satisfy the demand of the consumers. Energy is never used for the sake of consumption, but always to provide a certain service which satisfies a human need, for example mobility, cooking, or illumination. To meet these demands, primary energy resources enter the energy system at the top (Figure 3). They are then converted and transported within the energy system until the energy carriers reach the consumers as final energy. Those are then converted to useful energy to provide the required services.

As shown in Figure 3, the energy system encompasses all the steps from the production, conversion to the end use of energy. The technical infrastructure for supplying customers with final energy is allocated to the energy sector. As the energy demand is determined by the required services, it is driven from bottom-up. The energy supply on the other hand, is determined top-down by the availability of resources and conversion processes [19].

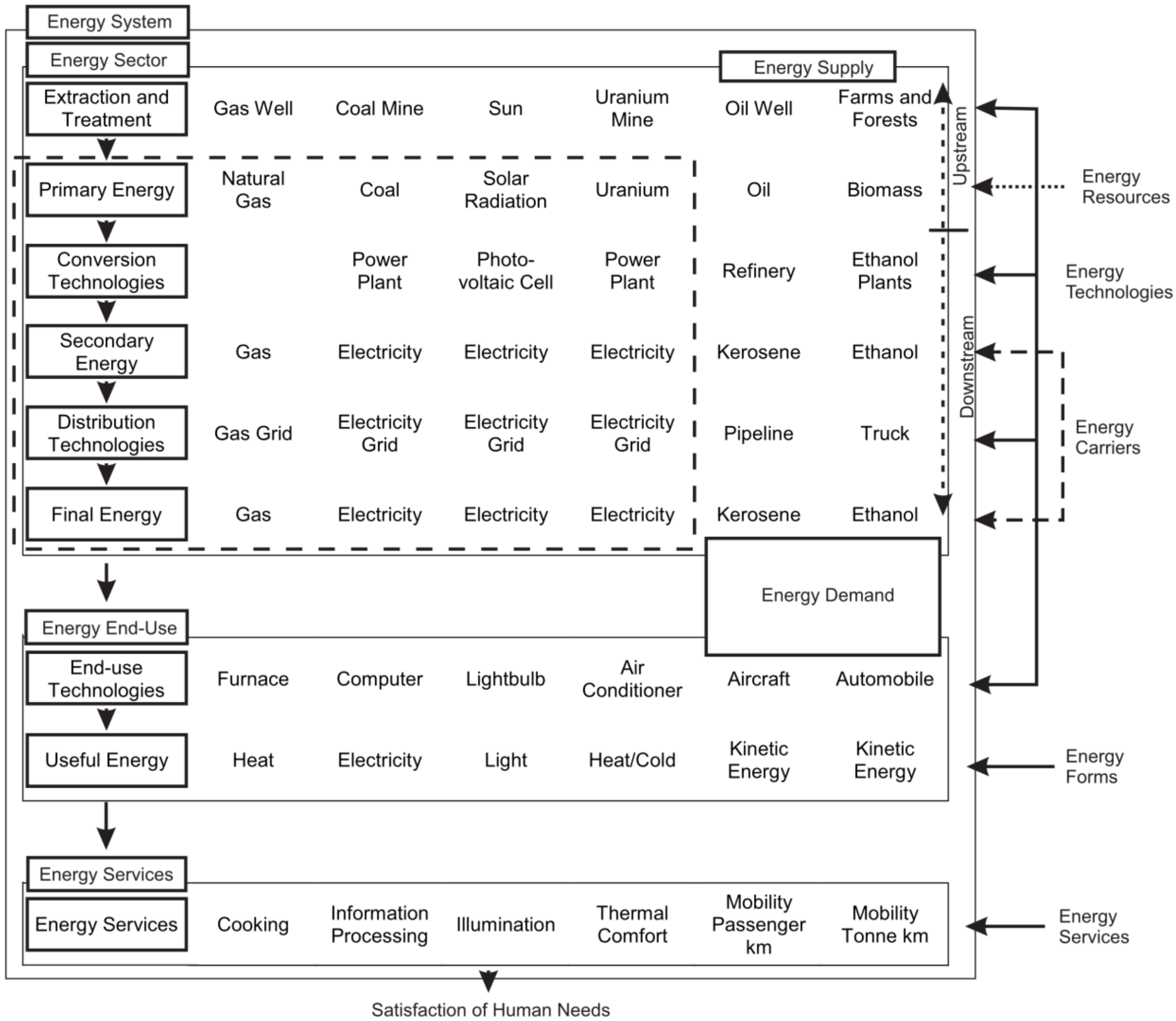

Figure 3: Schematic of energy flows through the energy systems. The flow of the different energy carriers through the stages are illustrative examples and are not fixed. [11], adapted from [19].

Despite efforts to decarbonize in recent years, energy supply is still mainly based on fossil fuels. Between 1973 and 2015 its share remained constant and is still above $80\ \%$. During the same period primary energy consumption has increased from $255\ EJ$ to $571\ EJ$ [20]. Energy demand forecasts estimate a further annual rise of approximately $1.5\ \%$ in the upcoming years because of population and economic growth [21]. Different studies expect the primary energy demand to reach between 770 and $1175\ EJ$ in 2050 (Table 1).

The high share of fossil fuels and the projected growth in global primary energy consumption (Table 1) call for urgent action in decarbonising the energy system and make a sustainable energy supply one of the major challenges for humankind in the 21st century. The resources and conversion processes used largely determine the losses and the efficiency of the energy system. Decarbonisation can be achieved by substituting fossil fuels by RES or by eliminating inefficiencies within the energy system. The inefficiencies can occur on all stages from primary energy to the final services. The further down the system they occur, the greater is their impact.

Table 1: Global primary energy consumption projections [22]

Organisation	2020 EJ	2030 EJ	2050 EJ	2100 EJ
BP (2011) [23]	565–635	600–760	-	-
EC (2006) [24]	570–610	650–705	820–935	-
EIA (2010) [25]	600–645	675–780	-	-
IAEA (2009) [26]	585–650	670–815	-	-
IEA (2010) [20]	-	605–705	-	-
IIASA (2007) [27]	555–630	-	800–1175	985–1740
Shell International (2008) [28]	630–650	690–735	770–880	-
WEC (2008) [29]	615–675	700–845	845–1150	-
Tellus Institute (2010) [30]	504–644	489–793	425–1003	243–1200

Tracking global energy flows was subject to intensive research in recent years to identify and eliminate those inefficiencies. Data from the “Global Energy Assessment” [19] show that in 2005 the worlds primary energy consumption was $496\ EJ$ [19]. The efficiency from primary to final energy was about $67\ \%$, for the efficiency from final to useful energy a global average of $51\ \%$ was estimated. Of the primary energy originally used, only $169\ EJ$ were used as usable energy.

Another study carried out by Cullen [18] also used 2005 data[1] to create a Sankey-diagram of the exergy flows (also called Grassmann-diagram) in the world’s energy system (Figure 4). The average exergy efficiency from primary sources to useful energy is about $12\ \%$ (compared to an energy efficiency of $34\ \%$). However, the more interesting part in Figure 4 are the losses. More than $71\ \%$ of the total conversion losses are assigned to thermal processes, either by combustion or heat transfer. Almost all chemical energy sources (fossil fuels and biomass) are combusted before they become useful energy. This intermediate step generates high exergy destruction and losses (more details in Chapter 2.3, also compare exergy-to-energy ratios for

[1] The difference in primary energy consumption, both use data for 2005, can be explained using different references. Johansson et al. used [31, 32], while Cullen used [33].

chemical -energy carriers and heat in Table 3). This exergy-based view indicates efficiency potentials and shows losses not visible with a purely energy-based view.

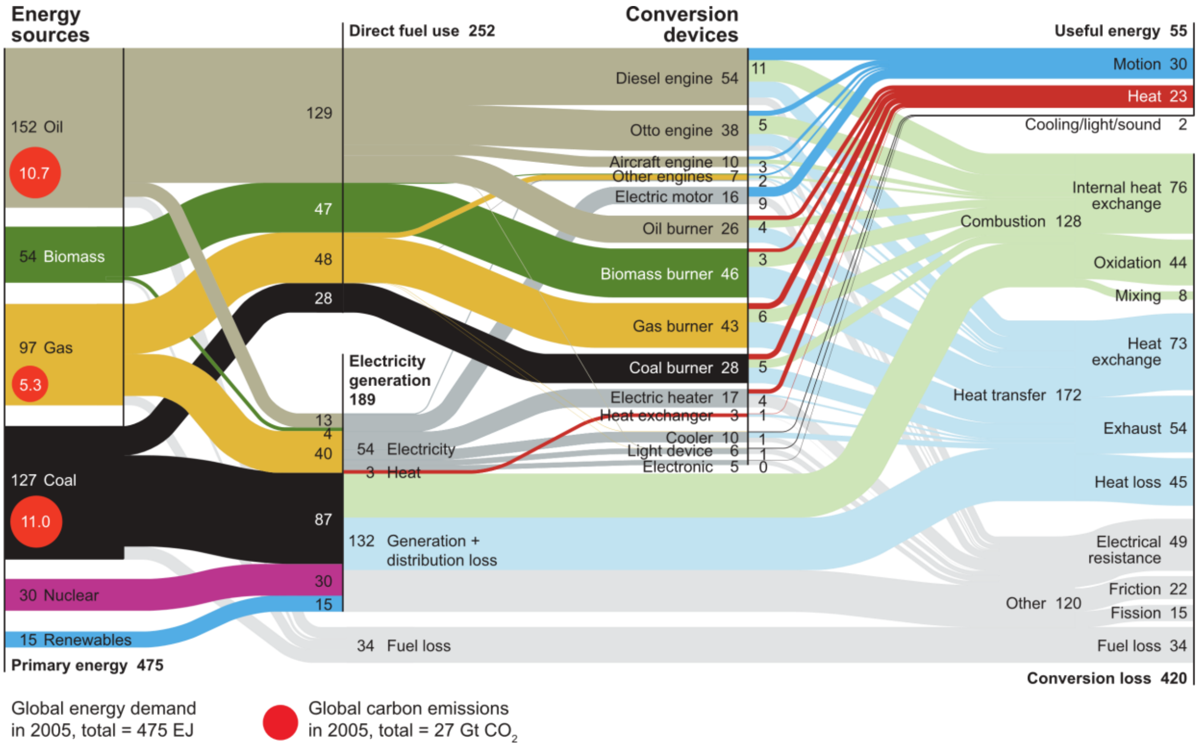

Figure 4: Global exergy flows - from source to useful energy [18]

While the Grassman-diagram indicates where the highest exergy losses occur, it provides no information on how fossil fuels can be replaced. In literature carbon capture, nuclear, and RES are discussed as options for a CO_2-neutreal energy supply. Even though carbon capture is seen as a vital solution to reach the 2°C goal, out of 37 commercial carbon capture projects only 17 are in operation and 4 are under construction [34]. However, for all but one of these projects enhanced oil recovery is the primary task. For nuclear energy, as another CO_2-free energy source, no significant contribution to a low-carbon energy supply is expected in literature. For nuclear fission even the IAEA (International Atomic Energy Agency) does not project a significant future increase beyond its current share of 5.8% [26]. Nuclear fusion is far from commercial operation, for example the construction of the ITER (International Thermonuclear Experimental Reactor) research reactor is not scheduled to be completed until 2025 at the earliest [35]. Therefore, on the supply side renewable energy sources are seen as the most promising option for decarbonisation [22].

Table 2 shows the results of various recent studies on the worldwide technical potentials for solar, wind, hydro and biomass[2]. The renewable potentials of all studies are of a comparable magnitude. The data shows that the projected demand from the different scenarios in Table 1 could be met by RES only. However, the results in the table must be carefully interpreted. These studies do not consider the resource effort required to exploit these potentials, such as the plant itself, transmission lines, support infrastructure, etc. Therefore, the efforts and costs for the utilisation of the first and last EJ of the technical potentials will differ substantially [22].

Table 2: Selected published estimated technical RES potentials [22]

Study and year of estimate	Solar	Wind	Hydro	Biomass
	EJ	EJ	EJ	EJ
Sims et al. (2007) [36]	1650	600	62	250
Resch et al. (2008) [37]	1600	600	50	250
Cho (2010) [38]	>1577	631	50	284
Tomabechi (2010) [39]	1600	700	59	200
All studies range	1577–1650	600–700	50–62	200–284

In addition, the renewable potentials are also unevenly distributed among the different countries and also within them. This requires a spatially resolved view of the potentials. Especially in densely populated and highly developed countries, it is likely that the available potential is not sufficient to cover the energy demand [5]. In this case, efficiency measures and RES-imports from other countries are the only options for a country's decarbonisation [40].

2.3 Fundamentals of Exergy

The first law of thermodynamics describes the conservation of energy: energy can never be created or destroyed, but it can be converted. The second law describes the energy's ability to cause change and in which directions conversions are possible. It allows to calculate the true thermodynamic value of an energy carrier [41]. This thermodynamic value is also called "exergy" and describes the "technical working capacity". It was first mentioned by Rant in 1953 [42]. In general, energy E consists of exergy B and anergy A.

---

[2] Ocean energy and geothermal energy are not included in this table because of their lower potentials. Solar, wind, and hydro energy potentials refer to the produced electricity, for biomass they refer to the raw material before conversion.

$$E = A + B \quad (1)$$

In Equation (1) exergy is the theoretically extractable useful part of an energy carrier when brought to equilibrium with its surrounding, anergy cannot be further utilised.

In a process the exergy part of an energy carrier is exploited, until only anergy is left. While exergy is consumed during these processes, entropy is created. The second law indicates the irreversibility of natural processes, the convertibility of energy carriers, and provides information in which direction a process proceeds. Conversion processes can only take place from higher to lower exergy levels.

Energy carriers like electricity or mechanical work can be fully converted to any other form of energy. For heat the convertibility depends on the temperature levels of a heat reservoir and its surroundings. Different resources can contribute to the total exergy of a system (Table 3). Common to all is that exergy always requires a potential difference between system and environment. This environment is usually the reference state which is described by its pressure p_0, temperature T_0, and material composition $\nu_{i,0}$. Commonly this reference state is the "standard atmosphere".

Table 3: Exergy or exergy to energy ratios for different energy forms and carriers [43]

Energy form or carrier	Exergy B or exergy to energy ratio r
Potential energy	$r_{pot} = 1$
Kinetic energy	$r_{kin} = 1$
Physical energy	$B_{ph} = (h - h_0) - (T_0 s - T_0 s_0)$
Chemical energy	$r_{ch} = 0.8\ to\ 1$, depending on the composition
Pressure of an ideal gas	$B_p = nRT_0 \cdot \ln\left(\frac{p}{p_0}\right)$
Solar irradiation	$r_{sol} = 0.9327$
Radiation	$B_{rad} = 1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\left(\frac{T_0}{T}\right)$
Electricity	$r_{el} = 1$
Nuclear energy	$r_{nu} = 1$
Heat	$r_{th} = 1 - \frac{T_0}{T}$

For kinetic exergy, the system's speed relative to the environment is decisive, for potential exergy it is the difference in height of the system to the environment. In case of chemical exergy, it is the potential difference between fuel and reducing agent; usually it can be approximate by using the lower heating value [10]. Physical exergy depends on the pressure p and temperature T deviation to the ambient conditions (p_0, T_0). It can be calculated by the difference of enthalpy h, entropy s and temperature T to the environment conditions (h_0, s_0, T_0).

In general there exist two basic thermodynamic inefficiencies in energy systems: Exergy losses B_L and exergy destruction B_D (Figure 5 right) [44]. Exergy destruction is caused by entropy generation s_{gen} in irreversible thermodynamic processes. This relation can be described by the Guoy-Stodola theorem (Equation (2)). Exergy destruction always occurs when a highly valuable energy carrier is converted into another and heat is generated during this process, or in case heat is transferred between two media. Well known examples for exergy destruction are the combustion of chemical energy carriers like natural gas to provide hot water, or heat exchangers.

$$B_D = T_0 * s_{gen} \tag{2}$$

Exergy losses are exergy flows across the system boundaries to the environment, which cannot be further utilised within the system. They may consist of heat or physical flows. Examples are the surface losses of boilers or the condensate heat discharged with the cooling water from power plants.

Energy and exergy perspectives of a conversion process are illustrated in Figure 5. Energy E_C or exergy B_C are consumed in the process while the useful energy E_U or exergy B_U are produced. In case of the energy perspective only energy losses E_L occur. For exergy, exergy destruction B_D must be considered alongside to the losses B_L.

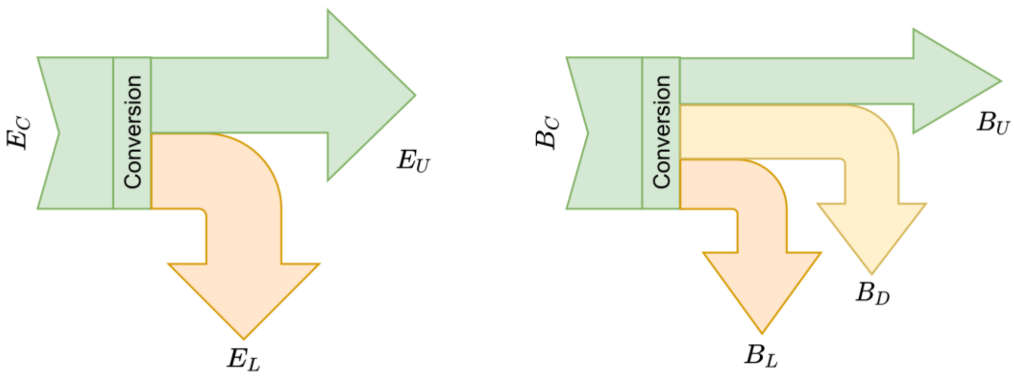

Figure 5: Energy losses (left) versus exergy losses and exergy destruction (right)

3 RESEARCH OBJECTIVES & METHODOLOGY

As described in the introduction, an expansion of RES and significant energy savings are necessary to achieve the climate goals and reach a sustainable society. Models can provide a better insight into the energy system and they support a better understanding of the interactions between the individual system components. This supports the efficient transformation to a sustainable energy system.

3.1 Research Objectives

Variable RES and energy storage pose new challenges for both current energy systems and energy system models. Assumptions and boundary conditions of models used in the past may not be valid any longer. Current energy system models predominantly use economic evaluation criteria. However, they cannot be used to identify inefficiencies and potential energy savings. In contrast to this, an exergetic evaluation criterion is very well suited to precisely investigate and overcome these points.

The main research topic of this thesis is the **optimisation of the exergy efficiency of municipal MES**. In this extensive field there are many individual research objectives that need to be answered. These are divided into three groups and presented in the following.

The first field of research objectives deals with the **municipal MES modelling**. The aim is to identify the main requirements for MES models for exergy optimisation. It includes the following research objectives:

- What are the decisive parameters to be modelled?
- Which simplifications need to be made?
- Which open source modelling frameworks are available?

The second field deals with the development of a basic methodology for **exergy optimisation**. This, of course, builds on the results of the first group. This group includes the following research objectives:

- System design: How should exergy efficient energy systems be designed? What is the best way to determine the optimal capacities of conversion units, RES and storage?
- System operation: How are the individual components optimally scheduled? How is the security of supply guaranteed?
- The relation between design and operation: How do design and operation affect each other?

The third field addresses the **application** of the developed methodology. Three case studies are carried out to answer the following research objectives:

- What is the impact of varying boundary conditions on the model's results?
- How can the spatial resolution be modelled and what influence does it have on the system design and operation?
- How do different load flow formulations perform and how do they affect the results and the computing time?

3.2 Methodology

This work draws on three papers which I authored, and which were published in scientific journals. The main aim of this thesis is the exergy optimisation of MES. To achieve this, first the requirements for a MES model are determined by an extensive literature study. Based on this, a methodology for the optimal design and operation of MES is developed. This methodology will then be applied to three case studies in the field of municipal energy systems. Different modelling aspects identified within the literature review will be investigated. The basic structure of this thesis and the connection between the individual papers is shown graphically in Figure 6.

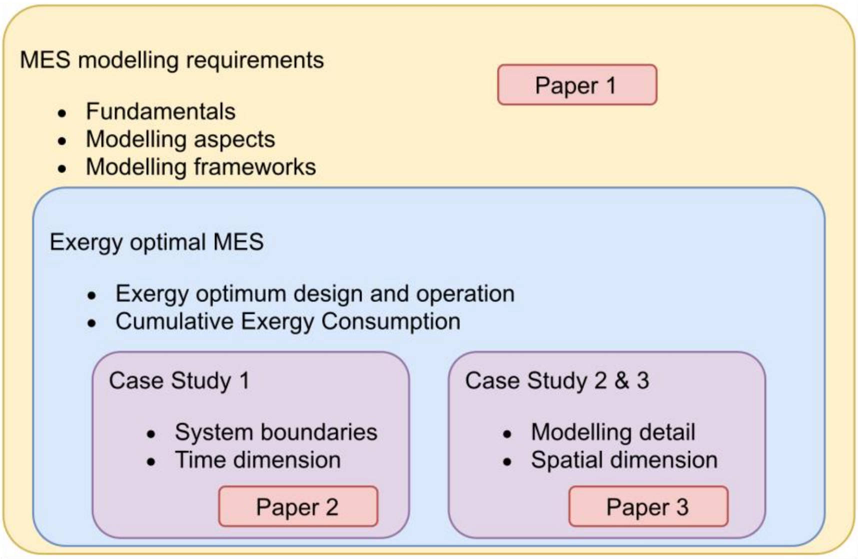

Figure 6: Graphical representation of the methodology and topics of the papers written.

The foundation was laid with an extensive literature review on the current developments, challenges and aspects of grid based MES-modelling. The requirements for MES models were derived from this work. Furthermore, different open source modelling frameworks were analysed to the applicability on MES. This work resulted in the Paper 1 [11]:

KRIECHBAUM, Lukas; SCHEIBER, Gerhild; KIENBERGER, Thomas: *Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges*. In: *Energy, Sustainability and Society* 8 (2018), Nr. 1, S. 244

Based on this knowledge, the Cumulative Exergy Consumption (CExC) methodology was selected for the simultaneous determination of optimal design and operation. It includes the exergy consumption for any energy carrier and material (e.g. for building storages and power plants) from the origin to consumption. The CExC-methodology was adapted to work with time resolved MES-models and used to investigate the parameters of the boundary conditions at the system boundaries. The results were published in paper 2 [45]:

KRIECHBAUM, Lukas; KIENBERGER, Thomas: *Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation*. In: *Energies* 13 (2020), Nr. 1, S. 182

Paper 3 uses the same methodology as Paper 2, but also takes the spatial resolution into account. For the necessary energy grids, models with different levels of detail were compared: network flow models and power flow models. The results were published in paper 3 [46]:

KRIECHBAUM, Lukas; GRADL, Philipp; REICHENHAUSER, Romeo; KIENBERGER, Thomas: *Modelling Grid Constraints in a Multi-Energy Municipal Energy System using Cumulative Exergy Consumption Minimisation*. In: *Energies* 13 (2020), Nr. 1, S. 182

Besides the main publications, the published conference papers, and co-authored papers (Appendix B) also contributed to this work. Papers [47, 48] provided the basic knowledge about exergy as evaluation criterion in municipal MES. Papers [49, 50] deal with spatial aggregation approaches and provide concepts for model simplification. Paper [8] addresses load flows in MES and supports the development of the optimal power flow model in Paper 3.

3.3 Contribution to the scientific knowledge

This thesis expands the scientific knowledge in the field of exergy optimisation of MES. A research field which has so far received very little attention in the literature. Except for some references such as [10] no publications on this subject could be found. Most applications of exergy are related to technical process analysis [41] or to the evaluation of resource consumption of entire countries [51]. An extensive review of existing literature about exergy applications on MES can be found in Papers 2 and 3. The contributions of the individual research fields to the scientific knowledge are listed below.

During the literature review in the first research area, existing literature was analysed and linked to gain new insights. This was necessary because previous reviews did not contain the required information about exergy optimisation of MES and suitable models. Those reviews focused on general energy system modelling [52, 53], MES alone [16, 54, 55], modelling tools [56, 57], or power system modelling [58]. An evaluation and comparison of different open source MES modelling tools also was not carried out before.

In the second research field, the CExC-methodology has been adapted for use with MES. Originally it was developed as an analysis tool for the evaluation of individual products [59] or processes [60]. In addition, it was used to determine the resource efficiency of entire countries [51, 61, 62]. In this work it is used for the first time as a decision criterion for optimal design and operation of MES.

In the third research field, the CExC methodology is applied to three different case studies. The first investigates the influence of different boundary conditions on the results. The second one examines the effects of modelling the spatial resolution. In the third one the model is extended by load flow equations for electricity, natural gas, and heat. This results in a so called optimal power flow model (OPF, see Chapter 4.2.3). There exist thousands of papers dealing with OPF for the optimum operation of the electric power system [63]. Some address the combined OPF for the operation of electricity and natural gas systems [64–66] , or even electricity, natural gas, and heat [7]. However, no reference is known where an OPF model is used together with an CExC-approach for the optimum design and operation of a MES.

4 MUNICIPAL MES MODELLING

In this thesis the main objective of MES modelling is to better understand how MES can contribute to a sustainable energy supply. For such a model to deliver valuable results, the following points should be considered:

- The modelling objective must be defined in advance
- The system to be modelled must be analysed and the key model parameters identified
- The system boundaries must be defined, and the boundary conditions be determined

Based on these results, suitable modelling concepts can be selected and permitted simplifications can be determined. The model can be created with the appropriate modelling tools.

The research objective of this thesis is exergy efficiency in municipal MES, with the focus on technical system design and operation as well as the integration of renewable resources. In the following, an in-depth analysis of municipal MES is carried out. Afterwards different simplification and modelling concepts are discussed, and suitable modelling frameworks are presented. The chapter concludes with a summary of the most important findings in the research field of **municipal MES modelling.**

4.1 Municipal Energy Systems

Municipal energy systems supply private households, small businesses, and public services with electricity and space heating. Typically, grid-based energy carriers like electricity, natural gas, and district heat are used for this task. Electricity and natural gas are usually obtained from higher network levels. District heat is supplied by waste heat or local plants like biomass boilers or combined heat and power (CHP) plants. More recently, RES such as PV or wind have also been increasingly added.

This makes municipal energy systems an illustrative example for a MES. Due to the well-developed energy networks they are excellently suited for the integration of decentralized RES. By linking electricity, heat, and natural gas networks through appropriate coupling technologies, the storage capacities available in one energy network can also be used by the others. This adds additional flexibility options to the MES. Flexibility options are dispatchable consumers, storages, or plants. By locally converting and storing energy, MES can relieve the strains on the energy transmission and distribution grids, which allows the share of RES to be further increased.

In grid-based municipal MES energy carriers are consumed to provide services like domestic heating, hot water, cooking, illumination or communication. The high share of demanded low temperature heat services, for example in Austria 33 % of the final energy consumption is used for domestic heating, hot water, and air conditioning [67], makes exergy a suitable assessment criterion to identify efficiency potentials. As a simplification, the demanded energy services will be combined to electricity and heat consumption. Different preconditions apply to both for the implementation of efficiency measures.

The well-developed electricity grid with its marginal losses makes electricity an easily transportable commodity. This ensures that a spatial decoupling of efficiency measures and consumption is possible. It means that efficiency measures can be implemented anywhere in the system, whether centralised or decentralised, and the whole system will benefit. If multiple efficiency measures are implemented, they are in operational competition with each other. Due to the bidirectional connection to the superior electricity grid, efficiency measures can even be implemented outside the system boundaries. However, this means that losses and inefficiencies outside the system boundaries must also be considered when assessing imported energy flows.

For heat the situation is different. Heat grids are only available in densely populated areas, they are unidirectional, and distribution losses are higher compared to electricity grids. Very often individual buildings or district heating grids are supplied just by a single or a few plants. This makes the heat supply a local matter. There exists no operational competition between the individual plants. To increase the efficiency in such a system, a local switch to more efficient conversion technologies is necessary. The decision on exergy consumption and efficiencies are made during the design process by the technology selection.

Another challenge is the fact that municipal energy systems consist of a large number of consumers, conversion units, renewable producers and storage facilities. These are distributed throughout the area and are connected by the energy grids. In addition, the short and long-term dynamics of RES, supply and demand require consideration of the time dimension. The temporal resolution must reflect the short-term dynamics, the period under consideration must be longer than the long-term dynamics.

Besides modelling the internal relations of the energy system, the boundary conditions also play a central role since MES are usually open systems with energy exchange over the system boundaries. Any imported energy carrier underwent some pre-treatment in which exergy is consumed. To avoid favouring energy imports over local production (or vice versa), exergy consumption for pre-treatment of imported energy carriers must be considered as well.

These different characteristics for heat and electricity supply as well as energy imports must be combined in a MES model. Therefore, the following points must be considered:

- Optimum design: Selection of the proper technology and the installed capacity.
- Optimum operation: Exergy efficient operation of the installed plants and storages.
- Assessment of energy imports: It must account for external losses and inefficiencies.
- Spatial dimension: resolution and coverage
- Temporal dimension: resolution and period

The consideration of all these points in their full level of detail leads to models with a complex mathematical description [68]. The solution of such models requires a high computational effort. Simplifications are necessary so that municipal MES models can be solved within a reasonable time. This concerns the space and time dimension as well as the modelling of the technical infrastructure.

4.2 Simplification & Modelling Concepts

The level of detail, input data and model formulation are a triangular relationship that affects computation time as well as accuracy and quality of results. Different concepts exist to reduce the resolution and complexity of space, time, and energy system components. In general, simpler models require less input data and have shorter computation times, but it must be assessed whether the simplifications made still lead to valid results. Highly detailed models promise more accurate results. However, they need large quantities of input data, their computational tractability is challenging, and solution times are longer.To still obtain feasible results from a simplified model, it is crucial to model the values which are relevant to the problem and not those that are easy to process and model [52].

4.2.1 Time

For energy systems mainly consisting of fully dispatchable generators the use of annual or seasonal demand and supply values was sufficient (a so-called *energy-based perspective*) [16]. Strongly fluctuating RES are expected to be the backbone of future municipal energy systems. They, together with a volatile energy consumption, require the consideration of the temporal variability (a so-called *power-based perspective)* [11]. This requires higher time resolutions and longer investigation periods, to account for short term and seasonal effects.

Finding a proper temporal resolution that fits all subsystems in a municipal MES is a challenge. Figure 7 shows that the required time scales for electricity, gas, and heating systems, which are typically for municipal MES models, are different. For integrated MES-models including RES a 15-minute interval is suggested [54]. In interlinked models appropriate temporal resolutions can be used for each subsystem. However, then the information flow from one to the other subsystem poses a challenge [69]. To model seasonal effects, consideration periods of at least one year are necessary.

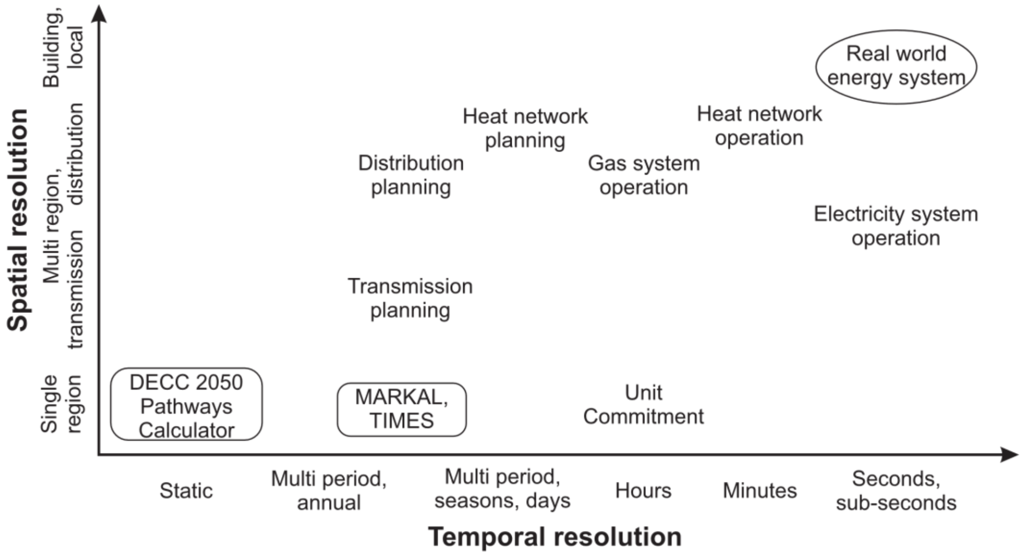

Figure 7: The different spatial and temporal scales required for MES planning and operation and current MES model resolutions. Adapted from [16]

4.2.2 Space

Municipal energy systems cover not only the densely populated central areas but also the sparsely populated periphery. The different energy grids do not cover all areas to the same extent. When modelling the spatial dimension, two points are addressed:

- The modelling of grid coverages and limitations due to maximum capacities for energy transport.
- Model simplification through spatial aggregation of RES, conversion units, storages, and consumers.

The first point only needs to be considered in case it has a significant impact on the results. The second one helps to keep computation times short. A spatial aggregation concept is the cellular approach [49]. Based on local conditions, a cellular mesh is superimposed over the studied area. Intracellular energy flows are neglected and all consumers, producers, grid connections etc. within one cell are lumped in its centre.

Because the spatial resolution and coverage has such a great impact on the calculation time, it also influences the possible mathematical formulation of the energy system's components (Figure 8). In general, current MES models which cover spatial dimensions greater than several buildings use simplified modelling approaches with a linear or mixed integer linear mathematical problem formulations [70].

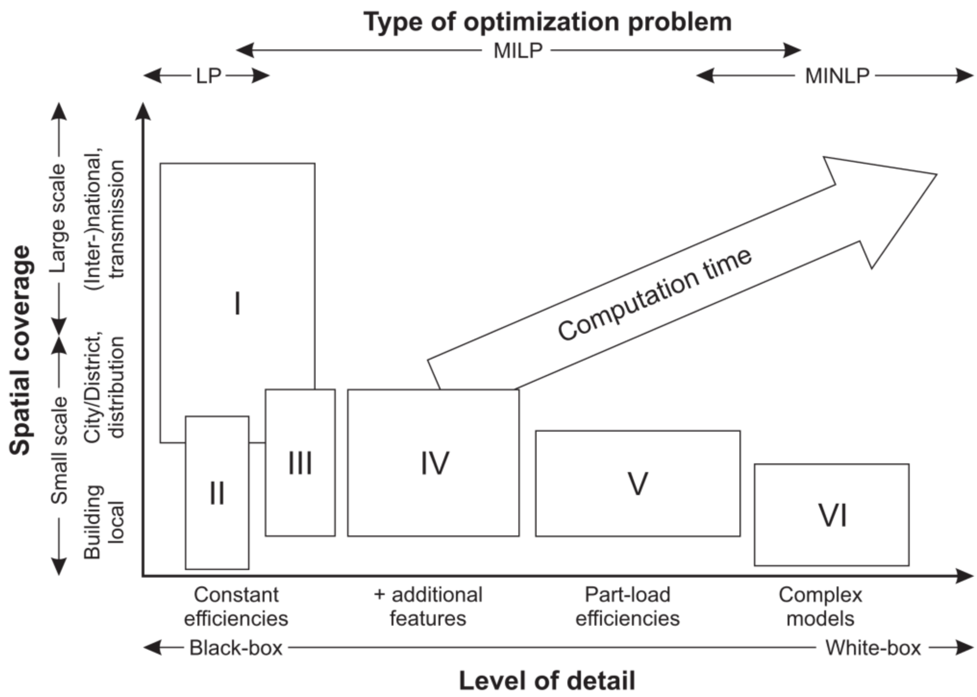

Figure 8: Spatial coverage, model level of detail and typical optimisation problem formulation. Classification of existing MES models according to their level of detail and spatial resolution[3]. Adapted from [70]

4.2.3 Modelling concepts

The entire technical infrastructure from energy conversion to storage and transport must be considered in MES models. Each individual component has different mathematical requirements for modelling. However, only linear or mixed integer linear problem formulations are proposed for municipal MES-models (Figure 8). To combine all requirements into one model, two general approaches are suggested: the integrated approach and co-simulation. In the former, all components are modelled with a single framework and solved together. Therefore, the very heterogeneous equations of the individual system components all must be transformed into the selected modelling framework. In the latter case the components are modelled in their dedicated tool and coupled by a superordinate unit. This means a reduced effort in component modelling, but at the expense of the linking effort.

There are formalised concepts for modelling the individual components, such as: the energy hub [7], the power node [71], the microgrid [72], or the virtual power plant [73] modelling concept. The most versatile one is the energy hub, which is also used for this work. An energy

[3] I: large-scale grid studies relying on simplified models, II: simple tools for quick assessments of small-scale energy systems, III: building and city district energy system design studies with simplified models, IV: on-site energy system studies with additional features, V: mixed-integer linear programming with part-load efficiencies and VI: mixed-integer non-linear programming with complex models.

hub serves as a general interface between the different energy grids and the consumers and producers. It describes the energy conversion from one to another energy carrier (Figure 9). An energy hub can have one or multiple inputs and outputs and comprises of one or multiple conversion units. Energy conversion and transport is mostly described by constant efficiencies, but other mathematical formulations are possible as well. Storages are described by a differential energy balance, accounting for inflow and outflow losses as well as stand-by losses.

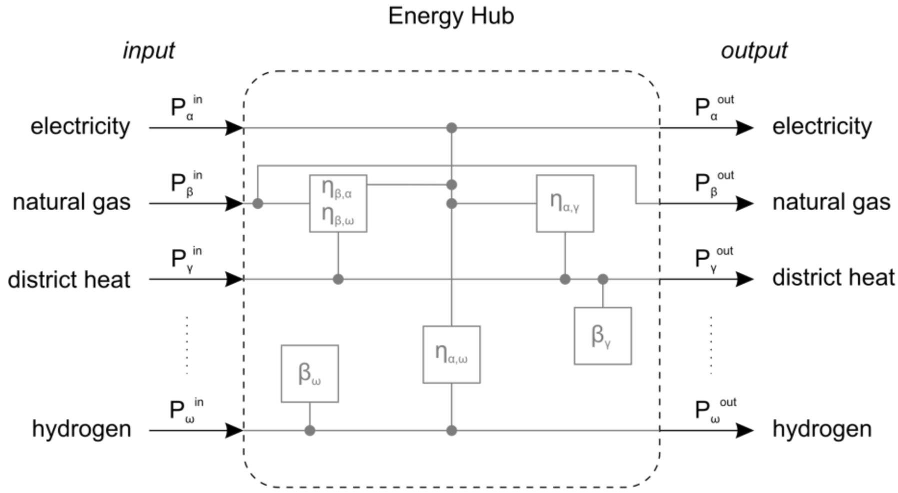

Figure 9: Example of an energy hub that contains converters ($\eta_{\alpha,\beta}$) and storage (β_α). Power from the input is converted to meet the load. $\alpha, \beta, \ldots, \omega$ are the different energy carriers. Adapted from [74]

Energy grids are necessary to connect consumers, producers, conversion units, and storages. There exist different levels of detail for grid modelling. In simplified network flow (NF) models losses are modelled by their conversion efficiency. A general model is suited for any energy carrier. Power flow (PF) models consider the physical laws driving the flows (e. g. voltage and pressure). Due to the different physical laws, specific models for each energy carrier are necessary [7].

Electric power flows can be modelled using AC (alternating current) and DC (direct current) representations. AC models consider active and reactive power flows. The AC representation leads to non-linear models and makes solving them for large scale electricity systems still a challenge [75]. Depending on requirements, resistance or reactance can be neglected in DC models. This leads to linear models which can be solved more easily.

Power flows calculations for heat and natural gas must consider pressure and heat losses. In integrated MES models the non-linear relation between flow and pressure loss requires either linearization or a nonlinear problem formulation. In case of using the linepack as flexibility option for the electricity grid, full transient representations of heat or gas flows are necessary [76].

4.3 Open source Modelling Frameworks

For modelling the case studies, a tool was sought that best meets the requirements or can be adapted to them with manageable effort. In the past, MES modelling tools were developed only for internal use in companies and research organisations [77]. Recently this has changed and there is now a wide variety of suitable modelling tools available. Many of them are open source [78], which means that their source code is freely accessible and that they can be adapted to the requirements needed.

Three open source modelling frameworks have proven to be suitable for the requirements of MES exergy optimisation:

Calliope is developed by the University of Cambridge and the ETH Zürich. For modelling the energy system's components it uses a generalised version of the power nodes modelling concept [71]. It is written in Python and allows linear and mixed integer linear model formulations. Framework (code) and model (data) are strictly separated. The focus is put on the modelling of spatial and temporal resolution, the ability to calculate and compare a large number of scenarios, and the greatest possible transparency of the model [79]. It covers all important requirements for exergy optimisation.

oemof (modular open source framework to model energy supply systems) is developed by the Reiner Lemoine Institut and the Center for Sustainable Energy Systems at Flensburg University of Applied Sciences. It incorporates all components necessary for MES exergy optimisation. The framework is written in Python and its object-oriented approach and modular structure make it easily adaptable to different requirements. oemof uses a modelling concept inspired by the energy hub and processes linear and mixed integer linear model formulations. It supports high spatial and temporal resolutions and the interlinking of different energy sectors and energy carriers [80].

urbs is developed by the Technical University of Munich. Its source code is also written in Python and it can solve linear model formulations. It was developed for capacity expansion and unit commitment in distributed energy systems, with a focus on storage sizing and operation [81]. It includes all necessary components for MES-modelling and allows an exergy assessment.

All models include the basic requirements such as spatial and temporal resolution, the basic infrastructure components (energy conversion, transport, storage, import, consumption, and renewable energy production) and allow exergetic design and operation optimisation. In addition, the frameworks also have unique features [11]. Calliope supports the multi scenario calculation and the definition of ramp rates for the individual components. oemof allows ramp rates only for storages, but additionally up and down times for all components can be defined. urbs has the most comprehensive economic model, allows to model demand response, and supports multi scenario calculations.

oemof was chosen to model the case studies. The modelling concept based on the energy hub and the modular approach were decisive for the choice. The latter one facilitates the integration of own components and makes the framework most flexible and adaptable for different tasks. The code base is maintained by an active development team, questions are answered by an active community.

4.4 Conclusion

The concluding remarks of this chapter contain the answers to the research objectives from the first research field **municipal MES modelling**. They are supported by content from Paper 1 and discussed below. The most important findings were:

- Since energy system design and operation are closely linked, the decisive parameters in municipal MES are the installed capacities of the individual components and their operational states over time. An efficient system operation is only possible if the design allows it.
- When considering high shares of RES in energy system models, the temporal variability of RES also calls for combined design and operation models.
- The model type and the modelled parameters must suit the modelling scope to provide feasible results. The parameters relevant to the task must be modelled and not those which are easy to model. The chosen model type must support a mathematical model formulation to model the system's internal (physical) relationships. Simplifications made must be permissible and the resulting error must be estimated.
- In municipal MES-models simplifications are necessary. The model formulation, level of detail, available input data, spatial coverage and resolution, and time horizon and resolution have a strong impact on computation times.
- The selection of the system boundaries and the input parameters is a critical point and can easily lead to biased results. They must be chosen with respect to the modelling objective. The quality of the input parameters must be taken into account in the evaluation of results and the conclusions drawn from them, since they are directly linked.
- Several open source modelling frameworks were tested and assessed. One of it, oemof (open energy modelling framework), was selected for modelling the case studies. It allows to solve linear and mixed integer linear problems.

5 EXERGY EFFICIENT DESIGN AND OPERATION OF MUNICIPAL ENERGY SYSTEMS

For an exergy optimisation of a municipal energy system, a MES model must be combined with an exergetic evaluation approach. So far, various tools and methods of exergy analysis have been developed [43, 82]. They include simple exergy efficiency calculations, thermoeconomics [41], extended exergy analysis [83], the exergetic cost theory [84, 85], and the cumulative exergy consumption [59]. The one that fits best to the MES-modelling requirements stated in Chapter 4.1 is the cumulative exergy consumption (CExC) methodology. It considers all exergetic efforts for energy import, the energy system's infrastructure, and the operation.

In the following, the CExC-methodology is presented first. Then the mathematical model description which is used to model the case studies is explained. At the end of the chapter, the most important findings from the exergy optimisation and the case studies are discussed.

5.1 Cumulative Exergy Consumption

Analysis of technical systems is probably the widest application of exergy [43]. The flow of exergy B (including all forms, B_{pot}, B_{kin}, B_{ph}, etc.) into and through the individual technical processes is analysed and exergy destruction and losses are illustrated. This information is then used to identify efficiency measures. However, this methodology does not account for any exergy losses before an energy carrier enters the system, and the generally higher resource effort to build more efficient plants [86].

$$B = B_{pot} + B_{kin} + B_{ch} + B_{ph} + \dots \tag{3}$$

The cumulative exergy consumption method, invented by Szargut [87] in 1957, addresses exactly this issue. It includes the exergy losses and destruction along all processes from the raw material to the final product or service. It therefore quantifies the exergy expenditures required to produce a single product or service unit. It is defined as its exergy content B, the exergy destruction $B_{D,p}$, the exergy losses $B_{L,p}$, and all other expenditures $B_{exp,p}$ (e.g. for conversion and transport infrastructure) which occur throughout the steps p of the production process PP. All these expenditures may occur "directly or indirectly, in the extraction, preparation, transportation, pre-treatment and manufacturing process" [88].

$$B^{*} = B + \sum_{p \in PP} \left(B_{D,p} + B_{L,p} + B_{exp,p} \right) \tag{4}$$

In summary, the exergy content B describes the value of an energy carrier, the CExC B^* the exergy content and the exergetic effort to produce a unit of an energy carrier or a product.

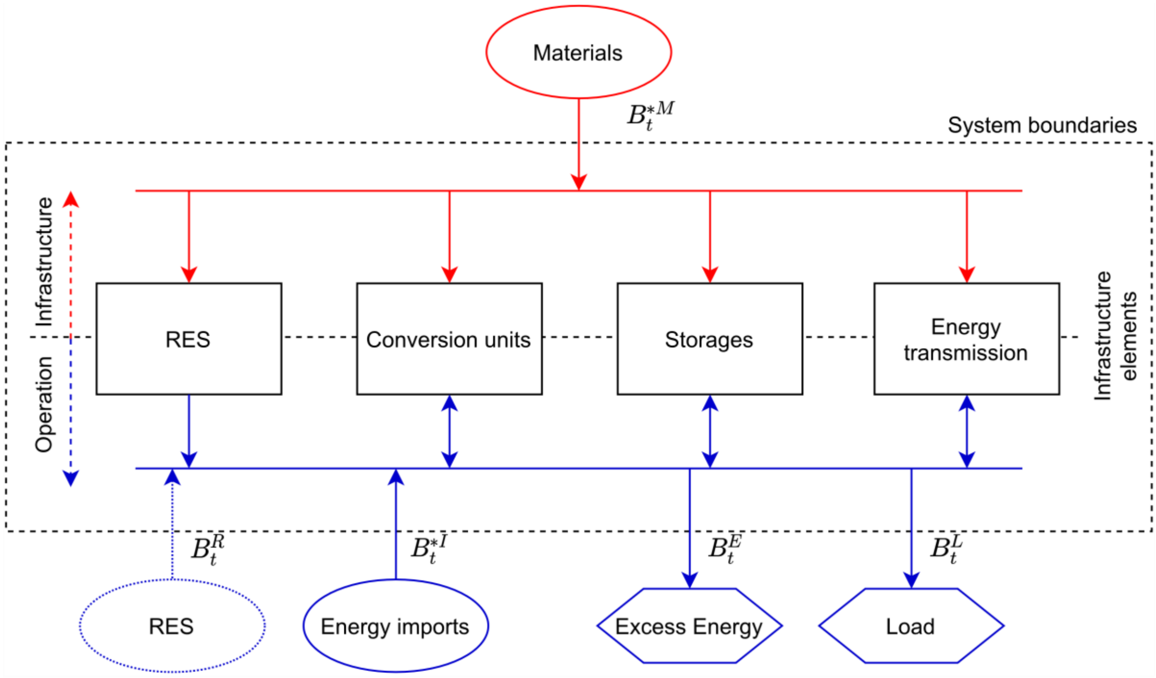

Figure 10: CExC expenditures and yields

CExC is a general methodology for resource accounting. Before an application, it must be specifically adapted to the desired application, in this case to a municipal MES. In MES exergy is consumed for infrastructure construction and system operation. The energy system's infrastructure (for RES, conversion units, storages, energy distribution) ensures that all customers are supplied with the desired form of energy. Exergetic expenditures B^{*M} arise to build this infrastructure due to the materials used (Figure 10). RES (B^R) and energy imports (B^{*I}) are required for the energy system's operation. Because they enter the energy system from outside, they cause additional expenditures. Energy exports (B^E) and loads (B^L) leave the energy system. They are the useful energy produced and are therefore treated as yields.

Summarised, there are infrastructure expenditures, operational expenditures, and operational yields. Infrastructure expenditures are needed to model the investment decisions, which is especially important for the technology selection in the heat sector. Additionally, they impact the unit expenditures. The higher the capacity factor of a plant, the lower the share of infrastructure expenditures in the unit expenditures. In general exergy efficient plants have higher infrastructure expenditures, and therefore need higher capacity factors to reach low unit expenditures. This fact might make less efficient technologies the better choice for applications with low capacity factors.

5.2 Mathematical Model Description

The optimum system design and operation of an energy system is reached when the CExC losses and destruction become a minimum. This task can be formulated as a general constrained optimisation problem [89]:

$$f = min\, F(x, y) \tag{5}$$

$$h(x, y) = 0 \tag{6}$$

$$g(x, y) \leq 0 \tag{7}$$

The linear objective function (Equation (5)) delivers a scalar value. The equality and inequality constraints (Equations (6) and (7)) may consist of continuous (x) and integer (y) variables.

For the implementation of the optimisation problem the open source energy systems model generator *oemof* (open energy modelling framework) is used. In the following, the derivation of the objective function is described first. It maps all CExC flows across the system boundaries. Then the mathematical description of the energy system's components, which consist of equality and inequality constraints, is presented. These are later used to model the different case studies.

5.2.1 Objective Function

For the optimum design the difference between total CExC expenditures B_t^{*X} and total exergy yields B_t^Y must become a minimum. The objective function can therefore be formulated:

$$min\, F(x, y) = B_t^{*X} - B_t^Y \tag{8}$$

Total expenditures B_t^{*X} comprise the expenditures for all individual components x_i, where X is the total set of all components. X can be further divided into five subsets, each consisting of its individual components: storages S (components s_i), conversion units C (components c_i), energy transmission T (components t_i), RES R (components r_i), energy imports I (components i_i). The sum of all subsets is then the total expenditure (Equation (9))

$$B_t^{*X} = \sum_{x \in X} B_x^{*X} = \sum_{s \in S} B_s^{*S} + \sum_{c \in C} B_c^{*C} + \sum_{t \in T} B_t^{*T} + \sum_{r \in R} B_r^{*R} + \sum_{i \in I} B_i^{*I} \tag{9}$$

For all components, the expenditures may comprise an investment and operating part. Therefore, for a general component x the CExC B_x^{*X} can be calculated according Equation (10). The first term describes the investment share, the second one the operational part.

$$B_x^{*X} = P_{x,inst}^X \cdot r_x^{*p,X} + \sum_t (P_x^X(t) \cdot r_x^{*X} \cdot \tau) \tag{10}$$

The descriptive parameters of an energy system are energy flows $P_x^X(t)$ and installed capacities $P_{x,inst}^X$ of the individual components. Therefore, it is reasonable to express CExC and exergy relative to these units. This can be achieved by using conversion factors r_x^{*X} to express the CExC per unit of energy E_x^X or installed capacity C_x^X (Equations (11) and (12)). In case of infrastructure investments, the lifetime T_{LT} is usually longer than the investigated period T. This is accounted for by using the equivalent periodic CExC-factor r^{*p} (Equation (12)).

$$r_x^{*X} = \frac{B_x^{*X}}{E_x} \tag{11}$$

$$r_x^{*X} = \frac{B_x^{*X}}{C_x^X}, \quad r_x^{*p,X} = r_x^{*X} \cdot \frac{T_x^X}{T_{x,LT}^X} \tag{12}$$

The same as for the expenditures applies for the total yields B_t^Y.The total set Y comprises the individual components y_i. It can be divided into two subsets: loads L (components l_i) and excess energy E (components e_i). The sum of the subsets is then the total yields (Equation (13)).The yields for an individual component only have an operational part and are calculated according to Equation (14). Analogous to the expenditures, an exergy factor r_y^Y is used to convert energy flows E_y^Y to exergy flows E_y^Y (Equation (15)).

$$B_t^{*Y} = \sum_{y \in Y} B_y^{*Y} = \sum_{l \in L} B_l^{*L} + \sum_{c \in C} B_e^{*E} \tag{13}$$

$$B_y^Y = \sum_t \left(P_y^Y(t) \cdot r_y^Y \cdot \tau\right) \tag{14}$$

$$r_y^Y = \frac{B_y^Y}{E_y^Y} \tag{15}$$

5.2.2 Energy System Components

The structure of an energy system is determined by its components and the connections between them. In case of modelling MES with *oemof*, the components in the same location (e.g. Cell 1) are connected via buses, the different locations are connected via energy grids (Figure 11). In mathematical terms, this structure is described by equality and inequality constraints. Any component type (conversion units, storages, RES, and energy grids) has its specific constraints, but there also exist constraints which apply to all components.

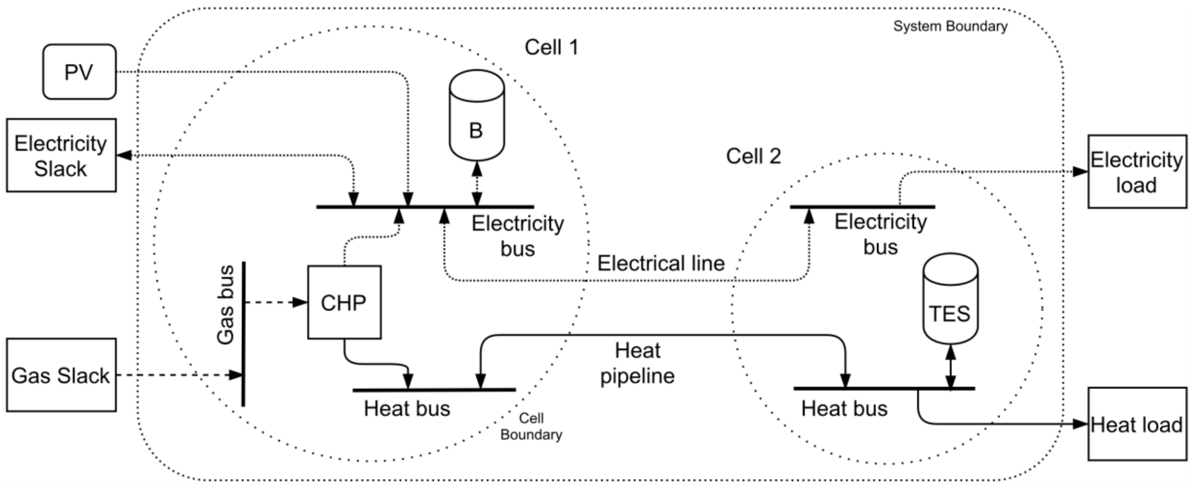

Figure 11: Example of a multi-cell MES model including energy imports and exports, RES, conversion units, storages and transmission grids [46]

The general constraints include the maximum installed capacity constraints. For all components, the actual power $P^X_{x,actv}$ must be lower than the installed capacity$P^X_{x,inst}$. The same applies to the storages, where the actual state of energy $SOE^S_{s,actv}$ must be lower than the installed $SOE^S_{s,inst}$.

$$P^X_{x,actv} - P^X_{x,inst} \leq 0 \tag{16}$$

$$SOE^S_{s,actv} - SOE^S_{s,inst} \leq 0 \tag{17}$$

All the following constraints are specific to their component. Conversion units can have single or multiple inputs $P_{c,in}$ and outputs $P_{c,out}$. Energy conversion itself is modelled by constant efficiencies η_c. In case of multiple inputs and outputs, the use of a conversion matrix $C_c$is recommended (Equation (18)).

$$\underbrace{\begin{pmatrix} P^{\alpha}_{c,out}(t) \\ P^{\beta}_{c,out}(t) \\ \vdots \\ P^{\omega}_{c,out}(t) \end{pmatrix}}_{P_{c,out}} = \underbrace{\begin{pmatrix} \eta^{\alpha,\alpha}_c & \eta^{\beta,\alpha}_c & \cdots & \eta^{\omega,\alpha}_c \\ \eta^{\alpha,\beta}_c & \eta^{\beta,\beta}_c & \cdots & \eta^{\omega,\beta}_c \\ \vdots & \vdots & \ddots & \vdots \\ \eta^{\alpha,\omega}_c & \eta^{\beta,\omega}_c & \cdots & \eta^{\omega,\omega}_c \end{pmatrix}}_{C_c} * \underbrace{\begin{pmatrix} P^{\alpha}_{c,in}(t) \\ P^{\beta}_{c,in}(t) \\ \vdots \\ P^{\omega}_{c,in}(t) \end{pmatrix}}_{P_{c,in}} \tag{18}$$

A differential energy balance is used to model the energy storages. It includes inflow $\eta_{s,in}$ and outflow losses $\eta_{s,out}$, as well as standby losses $\eta_{s,loss}$.

$$\Delta SOE_s(t) = \left[\eta_{s,in} \cdot P_{s,in}(t) - \eta_{s,out} \cdot P_{s,out}(t)\right] \cdot \tau - \eta_{s,loss} \cdot SOE_s(t-1) \tag{19}$$

Energy transmission can be modelled by the less detailed network flow models, or the more detailed power flow models. The network flow model works for any energy carrier and transmission losses are described by a constant transmission efficiency η^T_t.

$$P_{t,in}^{T}(t) \cdot \eta_t^T - P_{t,out}^{T}(t) = 0 \tag{20}$$

In power flow models the flows are not based on energy losses, but on physical principles. Therefore, additional constraints must be added. A linear electricity flow model is the DC-approximated power flow model [8]. It is assumed that the ohmic resistance R is negligibly small compared to the reactance X_t^T. This assumption is valid for high voltage overhead lines. In such cases the transmitted power $P_t^{T,el}$ only relates to the voltage angles $\Theta_{t,in}^{T,el}$ and $\Theta_{t,out}^{T,el}$, and the reactance $X_t^{T,el}$.

$$P_t^{T,el}(t) = \frac{\Theta_{t,in}^{T,el} - \Theta_{t,out}^{T,el}}{X_t^{T,el}} \tag{21}$$

For heat and gas, the load flows $P_t^{T,g,h}$ are based on the pressure differences ($p_{t,in}^{T,g,h}$, $p_{t,out}^{T,g,h}$), and the resistance $R_t^{T,g,h}$. The resistance itself is determined by the properties of the fluid Φ_t^F (pressure, temperature, composition) and the pipe Φ_t^P (diameter, length, roughness, etc.). However, as shown in Equation (22) this results in a nonlinear relation. To reduce the mathematical complexity of the model low and still account for the nonlinearity, a piecewise linearization is necessary (a detailed explanation can be found in [46]).

$$P_t^{T,g,h}(t) = \frac{\sqrt{p_{t,in}^{T,g,h} - p_{t,out}^{T,g,h}}}{R_t^{T,g,h}(\Phi_t^P, \Phi_t^F)} \tag{22}$$

Busses are the connecting element between the individual components. They balance all the incoming ($P_{b,in}^B$) and outgoing ($P_{b,out}^B$) load flows (Equation (23)). No losses occur. In case of using power flow equations, pressure and voltage angles must be balanced in an analogous way.

$$\sum_{in} P_{b,in}^B(t) - \sum_{out} P_{b,out}^B(t) = 0 \tag{23}$$

5.3 Conclusion

Three case studies were carried out using the presented CExC-minimisation methodology. The first comprises a single-node MES model which is used to investigate the effects of the variation of boundary conditions. The second examines the effects of spatial resolution in combination with limited transport capacities. For this purpose, a multi-node model with a network flow approach for modelling the energy transport is used. For the third case study the network flow approach is replaced by a more detailed power flow representation. The effects on results and computing time are investigated. Detailed case study descriptions and results can be found in Paper 2 and 3. In the following, the answers to the research objectives **exergy optimisation** and **applications** are discussed.

Based on the requirements for modelling exergy efficient municipal MES, the CExC methodology was selected and adapted. It is presented in the second paper and contributes to the research questions about the **exergy optimisation**:

- Only an exergy optimal designed MES allows the exergy optimal operation of the individual components. The parameter which connects design and operation are the unit expenditures. They include an infrastructure as well as an operational part and describe the exergy expenditures per unit of produced yield.
- To properly assess on-site efficiency measures of different conversion paths, it is also necessary to take into account exergy expenditures of the imported energy carriers. They usually underwent different pre-processing stages. Neglecting these may favour highly pre-processed resources, such as electricity, over local raw materials such as biomass.
- The most important points for exergy optimisation were the consideration of exergy losses outside the system boundaries, and the combined planning and operation approach for the system design. The first one makes on-site and external measures comparable. The second one is important because exergy efficiency in the heat sector, where the highest exergy losses occur, can mainly be reached by technology change. For example, through a switch to heat pumps, currently one of the most exergy efficient heat supply technology, which couple the electricity and heat sector.
- In general, exergy efficient technologies have higher infrastructure expenditures per unit of installed capacity than less exergy efficient technologies. The higher the capacity factor, the lower the share of the infrastructure expenditures on the unit expenditures. Overall, exergy-efficient technologies can achieve lower unit costs, but they require higher capacity factors to do so. Less exergy efficient technologies have higher operational expenditures, but at low capacity factors unit expenditures are usually lower (compared to exergy efficient technologies) due to the lower infrastructure expenditures.

The third research field comprises the **application** of the developed CExC-methodology to three case studies. Answering the research objectives is supported by content from Papers 2 and 3:

- Municipal MES are open systems with energy exchange over the system boundaries. In such cases local production is in competition with imports and exports. This means that the unit expenditures of local production must not exceed the unit expenditures for imports. Thus, the boundary conditions have a direct influence on the system design and operation. If external losses are not considered, local production will never be competitive, because there the losses are considered.

- Considering the spatial resolution accounts for limited energy transfer capacities and different energy network coverages. This adds more details and additional constraints to the model. This allows to consider that not all energy grids (electricity, natural gas and heat) are available in every region. In case the networks' limiting transmission capacities and energy losses affect the energy flows, different overall results will be achieved. If good quality data for network modelling are available, more accurate results can be reached.
- The modelling detail can have a big influence on computation time and results. For example, computation times for the linear network flow and the mixed integer linear power flow models used in Paper 3 variy between hours and days. While the overall results remained comparable, in some details the results differed widely. In the case of stub lines, there were no major differences between the two models, but in the meshed areas the power-flow model delivered significantly different results for installed capacities and plant and storage operation.

6 CONCLUSION

Exergy efficient municipal-MES are the main research field of this thesis. The first part is dedicated to the identification of the requirements for municipal MES models and the necessary simplifications. Based on these results, a methodology for the exergy-efficient design and operation of municipal MES was developed, the CExC-minimization. Three case studies were carried out applying this methodology on an exemplary municipal MES. In the first case study the influence of the boundary conditions was investigated. The second one addressed the impact of modelling the spatial resolution and limited energy transfer capacities. In the third case study a more detailed load flow formulation was used for modelling the energy transport. The effects on the calculation time and results were analysed.

The knowledge gained during this work helped to answer the research objectives and to draw the major conclusions. By combining several energy sectors in MES, significant efficiency potentials can be made available. The developed CExC-minimisation methodology demonstrates how these can be used most efficiently. The methodology itself is so general that it can be applied to any MES, from individual buildings to whole countries. In some cases, adjustments will be necessary depending on the task at hand.

Finally, for the application of the CExC methodology to municipal MES, three important points can be identified. The first point concerns the in-depth system understanding of municipal MES, which was necessary to create the model. In the heat sector, where usually the largest exergy losses occur, exergy savings are only possible by switching to more efficient technologies, for example CHPs or heat pumps. RES have lower capacity factors than conventional power plants and the exergy expenditures of installation may no longer be negligible compared to the operational expenditures. For these reasons, the exergy optimisation of municipal MES must always consider design and operation together.

The second point is the importance of boundary conditions in open systems, as is the case with municipal energy systems. In optimisation models, the most favourable option for the target function is always selected when several options are available. For exergy optimisation this means that an energy carrier is only produced locally if it is more exergy efficient than an import. If inappropriate exergy expenditures for external supply are determined, for example external losses are not considered, this will lead to biased results.

The third point concerns the level of detail and mathematical model formulation. The more detailed the model is, the more input data is required and the longer the computing time. Therefore, more accurate results can be achieved. This was examined using the example of spatial resolution and load flow modelling. A multi-node model with a simplified linear power flow formulation took a few hours to solve. The same model with a more detailed mixed integer linear power flow formulation took days to solve. The results for the whole system and the nodes connected via stub lines differed only slightly. However, the installed capacities and the operation of the components in the meshed nodes differed significantly. It is not possible to make a general recommendation on the level of detail required, as this always depends on the specific task.

7 OUTLOOK

Even though in this work a wide range of topics has been addressed and many research questions were answered, there are still gaps and opportunities for future research. They may address improvements to the methodology, the input data, the model formulation, the system boundaries, as well as the investigation of further case studies using the CExC-methodology.

In a first step further components for modelling can be added or existing ones can be modelled more precisely. If considering demand side management (DSM) in the model, flexible consumers can be modelled as well. This may reduce the necessary storage capacities. Further improvements include the implementation of additional technologies of conversion units, storages, and RES. A stochastic approach is also possible for RES, as this better reflects their natural characteristics.

In addition to considering more technologies and resources, further influencing factors from Figure 2 can be included into the model. However, any field requires its own modeling approach with its distinct mathematical formulation and the necessary input data. For integrated models, additional integrated fields must be simplified for common model formulation. The more interlinked a model is, the greater the computational effort required to solve the problem.

Another potential future field of research concerns the quality of input data. The CExC factors for the assessment of resource imports are given as an example. In this work they are assumed to be constant. Especially for electricity import this parameter will vary over the day and the year in a future energy system with high shares of RES. For the energy system components these are usually a function of the total installed capacity.

All three points mentioned above have in common that the level of detail increases and therefore more input data is needed. Very often this data is not available because it is not measured (e.g. high resolution load profiles of electricity and gas demand or RES production) [90], it is commercially confidential [55], is of doubtful quality, or relates to the future and is highly uncertain. If data is not available, it must be estimated or values from literature must be used. In such cases it must be evaluated whether models with higher details provide more accurate results than simplified models where all input data are known. The influence of these parameters and the model sensitivity to them can be determined by stochastic modelling or by using a Monte-Carlo analysis approach.

Since the CExC-minimization is a general methodology, future applications cover a wide field. It can be applied on various energy and production systems, ranging from single houses and small plants to larger systems like industrial parks or energy systems of countries. The more holistic the model is, and the more sectors are considered, the better results can be found, as only then additional synergies can be revealed.

8 REFERENCES

[1] *CO2 Emissions from Fuel Combustion 2017*. Paris, Lanham : Organization for Economic Cooperation & Development; Rowman & Littlefield Publishers, Incorporated [Distributor], 2017

[2] UNITED NATIONS FRAMEWORK CONVENTION OF CLIMATE CHANGE (Hrsg.): *United Nations Framework Convention on Climate Change* : *Adoption of the Paris agreement*. Paris : United Nations, 2015

[3] EUROPEAN COMMISSION (Hrsg.): *Energy Roadmap 2050* : *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. COM(2011) 885 final. Brussels, December 15, 2011

[4] EDENHOFER, Ottmar (Hrsg.): *Climate change 2014* : *Mitigation of climate change Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York NY : Cambridge University Press, 2014

[5] BRAUNER, Günther: *Energiesysteme* : *Regenerativ und dezentral*. Wiesbaden : Springer Fachmedien Wiesbaden, 2016

[6] MOHAMMADI, Mohammad ; NOOROLLAHI, Younes ; MOHAMMADI-IVATLOO, Behnam ; YOUSEFI, Hossein: *Energy hub* : *From a model to a concept – A review*. In: *Renewable and Sustainable Energy Reviews* 80 (2017), S. 1512–1527

[7] GEIDL, Martin: *Integrated Modeling and Optimization of Multi-Carrier Energy Systems*. Zürich, ETH Zürich. Dissertation. 2007

[8] BÖCKL, Benjamin ; GREIML, Matthias ; LEITNER, Lukas ; PICHLER, Patrick ; KRIECHBAUM, Lukas ; KIENBERGER, Thomas: *HyFlow—A Hybrid Load Flow-Modelling Framework to Evaluate the Effects of Energy Storage and Sector Coupling on the Electrical Load Flows*. In: *Energies* 12 (2019), Nr. 5, S. 956

[9] CONNOLLY, D. ; LUND, H. ; MATHIESEN, B. V. ; LEAHY, M.: *A review of computer tools for analysing the integration of renewable energy into various energy systems*. In: *Applied Energy* 87 (2010), Nr. 4, S. 1059–1082

[10] KRAUSE, Thilo ; KIENZLE, Florian ; ART, Simon ; ANDERSSON, Göran: Maximizing exergy efficiency in multi-carrier energy systems. In: *Energy Society General Meeting*, 2010, S. 1–8

[11] KRIECHBAUM, Lukas ; SCHEIBER, Gerhild ; KIENBERGER, Thomas: *Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges*. In: *Energy, Sustainability and Society* 8 (2018), Nr. 1, S. 244

[12] IEA-ETSAP: *MARKAL* : *MARket ALlocation* : IEA-ETSAP, 2008. URL http://iea-etsap.org/index.php/etsap-tools/model-generators/markal – Überprüfungsdatum 2017-12-04

[13] IEA-ETSAP: *TIMES* : *The Integrated MARKAL-EFOM System* : IEA-ETSAP, 2017 – Überprüfungsdatum 2017-12-04

[14] AGNEW, M. ; SCHRATTENHOLZER, L. ; VOSS, A.: *A Model for Energy Supply Systems Alternatives and their General Environmental Impact*. IIASA, Laxenburg, Austria, 1979

[15] MESSNER, S.: *User's Guide for the Matrix Generator of Message II. Parts I and II* : *Model Description and Implementation Guide, and Appendices*. IIASA, Laxenburg, Austria, 1984

[16] MANCARELLA, P. ; ANDERSSON, G. ; PECAS-LOPES, J. A. ; BELL, K.R.W.: Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities. In: *2016 Power Systems Computation Conference (PSCC)* : IEEE, 2016, S. 1–22

[17] HUNTINGTON, Hillard G. ; WEYANT, John P. ; SWEENEY, James L.: *Modeling for insights, not numbers: the experiences of the energy modeling forum*. In: *Omega* 10 (1982), Nr. 5, S. 449–462

[18] CULLEN, Jonathan ; HALL, Clare: *Engineering Fundamentals of Energy Efficiency*. Cambridge, University of Cambridge. PhD. 2009

[19] JOHANSSON, Thomas B. (Hrsg.): *Global Energy Assessment (GEA)* : *Toward a Sustainable Future*. 1. publ. Cambridge u.a. : Cambridge Univ. Press, 2012

[20] INTERNATIONAL ENERGY AGENCY: *Key world energy statistics* : *Also available on smartphones and tablets*. Paris, 2017

[21] LEWIS, Nathan S. ; NOCERA, Daniel G.: *Powering the planet* : *Chemical challenges in solar energy utilization*. In: *Proceedings of the National Academy of Sciences of the United States of America* 103 (2006), Nr. 43, S. 15729–15735

[22] MORIARTY, Patrick ; HONNERY, Damon: *What is the global potential for renewable energy?* In: *Renewable and Sustainable Energy Reviews* 16 (2012), Nr. 1, S. 244–252

[23] BP: *BP Energy Outlook 2030*

[24] EUROPEAN COMMISSION: *World Energy Technology Outlook - 2050 (WETO-H2)*. URL https://cordis.europa.eu/article/id/87905-the-future-of-energy. – Aktualisierungsdatum: 2008 – Überprüfungsdatum 2020-07-25

[25] U.S. ENERGY INFORMATION ADMINISTRATION: *International Energy Outlook 2010*

[26] *Energy, electricity and nuclear power estimates for the period up to 2030*. 2009 ed. Vienna : International Atomic Energy Agency, 2009 (Reference data series no. 1)

[27] RIAHI, Keywan ; GRÜBLER, Arnulf ; NAKICENOVIC, Nebojsa: *Scenarios of long-term socio-economic and environmental development under climate stabilization*. In: *Technological Forecasting and Social Change* 74 (2007), Nr. 7, S. 887–935

[28] SHELL INTERNATIONAL BV: *Shell energy scenarios to 2050*

[29] SCHIFFER, Hans-Wilhelm: *WEC energy policy scenarios to 2050*. In: *Energy Policy* 36 (2008), Nr. 7, S. 2464–2470

[30] RASKIN, Paul D. ; ELECTRIS, Christi ; ROSEN, Richard A.: *The Century Ahead* : *Searching for Sustainability*. In: *Sustainability* 2 (2010), Nr. 8, S. 2626–2651

[31] INTERNATIONAL ENERGY AGENCY: *Energy Balances of Non-OECD Countries* : *2005*

[32] ITERNATIONAL ENERGY AGENCY: *Energy Balances of OECD Countries* : *2005*

[33] INTERNATIONAL ENERGY AGENCY: *2005 Balance table for the world*

[34] BUI, Mai ; ADJIMAN, Claire S. ; BARDOW, André ; ANTHONY, Edward J. ; BOSTON, Andy ; BROWN, Solomon ; FENNELL, Paul S. ; FUSS, Sabine ; GALINDO, Amparo ; HACKETT, Leigh A. ; HALLETT, Jason P. ; HERZOG, Howard J. ; JACKSON, George ; KEMPER, Jasmin ; KREVOR, Samuel ; MAITLAND, Geoffrey C. ; MATUSZEWSKI, Michael ; METCALFE, Ian S. ; PETIT, Camille ; PUXTY, Graeme ; REIMER, Jeffrey ; REINER, David M. ; RUBIN, Edward S. ; SCOTT, Stuart A. ; SHAH, Nilay ; SMIT, Berend ; TRUSLER, J. P. Martin ; WEBLEY, Paul ; WILCOX, Jennifer ; MAC DOWELL, Niall: *Carbon capture and storage (CCS): the way forward*. In: *Energy & Environmental Science* 11 (2018), Nr. 5, S. 1062–1176

[35] CAMPBELL, D. J.: *The first fusion reactor: ITER*. In: *Europhysics News* 47 (2016), 5-6, S. 28–31

[36] SIMS, Ralph E.H. ; SCHOCK, Robert N. ; ADEGBULULGBE, Anthony ; FENHANN, Jørgen ; KONSTANTINAVICIUTE, Inga ; MOOMAW, William ; NIMIR, Hassan B. ; SCHLAMADINGER, Bernhard ; TORRES-MARTÍNEZ, JULIO , TURNER, CLIVE ; UCHIYAMA, Yohji ; VUORI, Seppo ; WAMUKONYA, Njeriö ; ZHANG, Xiliang: Energy supply. In: METZ, Bert (Hrsg.): *Climate change 2007* : *Mitigation of climate change : contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge : Cambridge University Press, 2007, S. 251–322

[37] RESCH, Gustav ; HELD, Anne ; FABER, Thomas ; PANZER, Christian ; TORO, Felipe ; HAAS, Reinhard: *Potentials and prospects for renewable energies at global scale*. In: *Energy Policy* 36 (2008), Nr. 11, S. 4048–4056

[38] CHO, Adrian: *Energy's tricky tradeoffs*. In: *Science* 329 (2010), Nr. 5993, S. 786–787. URL https://science.sciencemag.org/content/329/5993/786.summary?casa_token=yfemvv3pnwwaaaaa:6hoy6bmvplo0zvyhdo-k_bzxrmdfri3h_0eoxt8xifrnuqi2rwuawlpsp5znjmtuakrkbrjsddixww

[39] TOMABECHI, Ken: *Energy Resources in the Future*. In: *Energies* 3 (2010), Nr. 4, S. 686–695. URL https://www.mdpi.com/1996-1073/3/4/686

[40] SEJKORA, Christoph ; KÜHBERGER, Lisa ; RADNER, Fabian ; TRATTNER, Alexander ; KIENBERGER, Thomas: *Exergy as Criteria for Efficient Energy Systems—A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential*. In: *Energies* 13 (2020), Nr. 4, S. 843

[41] TSATSARONIS, George: *Thermoeconomic analysis and optimization of energy systems*. In: *Progress in Energy and Combustion Science* 19 (1993), Nr. 3, S. 227–257

[42] RANT, Zoran: *Exergie - ein neues Wort für die Technische Arbeitsfähigkeit*. In: *Forschung auf dem Gebiete des Ingenieurwesens 22* 22 (1956), Nr. 1, S. 36–37

[43] DEWULF, Jo ; VAN LANGENHOVE, Herman ; MUYS, Bart ; BRUERS, Stijn ; BAKSHI, Bhavik R. ; GRUBB, Geoffrey F. ; PAULUS, D. M. ; SCIUBBA, Enrico: *Exergy: Its Potential and Limitations in Environmental Science and Technology*. In: *Environmental Science & Technology* 42 (2008), Nr. 7, S. 2221–2232

[44] TSATSARONIS, George: *Definitions and nomenclature in exergy analysis and exergoeconomics*. In: *Energy* 32 (2007), Nr. 4, S. 249–253

[45] KRIECHBAUM, Lukas ; KIENBERGER, Thomas: *Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation*. In: *Energies* 13 (2020), Nr. 1, S. 182

[46] KRIECHBAUM, Lukas ; GRADL, Philipp ; REICHENHAUSER, Romeo ; KIENBERGER, Thomas: *Modelling Grid Constraints in a Multi-Energy Municipal Energy System Using Cumulative Exergy Consumption Minimisation*. In: *Energies* 13 (2020), Nr. 15, S. 3900. URL https://www.mdpi.com/1996-1073/13/15/3900

[47] KRIECHBAUM, L. ; BÖCKL, B. ; VOPAVA, J. ; KIENBERGER, T.: SmartExergy – Primary Energy Efficient and Hybrid Grid Solutions for Municipal Energy Supply Systems. In: SCHULZ, Detlef

(Hrsg.): *NEIS Conference 2016*. Wiesbaden : Springer Fachmedien Wiesbaden, 2017, S. 133–139

[48] KRIECHBAUM, Lukas ; HEINRICH, Daniel ; KIENBERGER, Thomas: Werkzeug zur Ermittlung der Exergieeffizienz von Fernwärmesystemen. In: *10. Internationale Energiewirtschaftstagung*. Wien, 2017

[49] BÖCKL, Benjamin ; KRIECHBAUM, Lukas ; KIENBERGER, Thomas: Analysemethode für kommunale Energiesysteme unter Anwendung des zellularen Ansatzes. In: Institut für Elektrizitätswirtschaft und Energieinnovation (Hrsg.): *14. Symposium Energieinnovation* : *Energie für unser Europa*. Graz : TU Graz, 2016

[50] VOPAVA, Julia ; BÖCKL, Benjamin ; KRIECHBAUM, Lukas ; KIENBERGER, Thomas: *Anwendung zellularer Ansätze bei der Gestaltung zukünftiger Energieverbundsysteme*. In: *e & i Elektrotechnik und Informationstechnik* 134 (2017), Nr. 3, S. 238–245

[51] ERTESVÅG, Ivar S.: *Society exergy analysis: a comparison of different societies*. In: *Energy* 26 (2001), Nr. 3, S. 253–270. URL http://www.sciencedirect.com/science/article/pii/S0360544200000700

[52] PFENNINGER, Stefan ; HAWKES, Adam ; KEIRSTEAD, James: *Energy systems modeling for twenty-first century energy challenges*. In: *Renewable and Sustainable Energy Reviews* 33 (2014), S. 74–86

[53] HALL, Lisa M.H. ; BUCKLEY, Alastair R.: *A review of energy systems models in the UK: Prevalent usage and categorisation*. In: *Applied Energy* 169 (2016), S. 607–628

[54] VAN BEUZEKOM, I. ; GIBESCU, M. ; SLOOTWEG, J. G.: A review of multi-energy system planning and optimization tools for sustainable urban development. In: *2015 IEEE Eindhoven PowerTech*, 2015, S. 1–7

[55] MANCARELLA, Pierluigi: *MES (multi-energy systems)* : *An overview of concepts and evaluation models*. In: *Energy* 65 (2014), S. 1–17

[56] KEIRSTEAD, James ; JENNINGS, Mark ; SIVAKUMAR, Aruna: *A review of urban energy system models* : *Approaches, challenges and opportunities*. In: *Renewable and Sustainable Energy Reviews* 16 (2012), Nr. 6, S. 3847–3866

[57] WIESE, Frauke ; HILPERT, Simon ; KALDEMEYER, Cord ; PLEßMANN, Guido: *A qualitative evaluation approach for energy system modelling frameworks*. In: *Energy, Sustainability and Society* 8 (2018), Nr. 1, S. 211

[58] SYRANIDIS, Konstantinos ; ROBINIUS, Martin ; STOLTEN, Detlef: *Control techniques and the modeling of electrical power flow across transmission networks*. In: *Renewable and Sustainable Energy Reviews* 82 (2018), S. 3452–3467

[59] SZARGUT, Jan ; MORRIS, David R.: *Cumulative exergy consumption and cumulative degree of perfection of chemical processes*. In: *International Journal of Energy Research* 11 (1987), Nr. 2, S. 245–261

[60] ZIĘBIK, Andrzej ; GŁADYSZ, Paweł: *Analysis of the cumulative exergy consumption of an integrated oxy-fuel combustion power plant*. In: *Archives of Thermodynamics* 34 (2013), Nr. 3, S. 105–122

[61] SUN, Boxue ; NIE, Zuoren ; GAO, Feng: *Cumulative exergy consumption (CExC) analysis of energy carriers in China*. In: *International Journal of Exergy* 15 (2014), Nr. 2, S. 196

[62] UKIDWE, Nandan U. ; BAKSHI, Bhavik R.: *Industrial and ecological cumulative exergy consumption of the United States via the 1997 input–output benchmark model*. In: *Energy* 32 (2007), Nr. 9, S. 1560–1592

[63] FRANK, Stephen ; REBENNACK, Steffen: *An introduction to optimal power flow: Theory, formulation, and examples*. In: *IIE Transactions* 48 (2016), Nr. 12, S. 1172–1197

[64] SHAO, Chengcheng ; WANG, Xifan ; SHAHIDEHPOUR, Mohammad ; WANG, Xiuli ; WANG, Biyang: *An MILP-Based Optimal Power Flow in Multicarrier Energy Systems*. In: *IEEE Transactions on Sustainable Energy* 8 (2017), Nr. 1, S. 239–248

[65] UNSIHUAY, Clodomiro ; LIMA, J. W. Marangon ; SOUZA, A. ZambroniC. de: Modeling the Integrated Natural Gas and Electricity Optimal Power Flow. In: *IEEE Power Engineering Society general meeting, 2007* : *24 - 28 June 2007, [Tampa, FL*. Piscataway, NJ : IEEE Service Center, 2007, S. 1–7

[66] XU, Xiandong ; LI, Kang ; LIU, Yang ; JIA, Hongjie: Integrated optimal power flow for distribution networks in local and urban scales. In: *2016 UKACC 11th International Conference on Control (CONTROL)* : IEEE, 2016 - 2016, S. 1–6

[67] STATISTIK AUSTRIA: *Nutzenergieanalyse (NEA) 2017*. URL http://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/nutzenergieanalyse/index.html – Überprüfungsdatum 2018-01-18

[68] PALENSKY, Peter ; DIETRICH, Dietmar: *Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads*. In: *IEEE Transactions on Industrial Informatics* 7 (2011), Nr. 3, S. 381–388

[69] WELSCH, Manuel ; MENTIS, Dimitris ; HOWELLS, Mark: Long-Term Energy Systems Planning. In: JONES, Lawrence E. (Hrsg.): *Renewable Energy Integration* : Elsevier, 2014, S. 215–225

[70] THIEM, Sebastian: *Multi-modal on-site energy systems* : *Development and application of a superstructure-based optimization method for energy system design under consideration of part-load efficiencies*. München, Technische Universität München. PhD. 2017

[71] HEUSSEN, Kai ; KOCH, Stephan ; ULBIG, Andreas ; ANDERSSON, Göran: Energy storage in power system operation : The power nodes modeling framework. In: *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, 2010, S. 1–8

[72] ASMUS, Peter: *Microgrids, Virtual Power Plants and Our Distributed Energy Future*. In: *The Electricity Journal* 23 (2010), Nr. 10, S. 72–82 – Überprüfungsdatum 2014-11-18

[73] CORERA, José (Hrsg.): *FENIX* : *Flexible Electricity Networks to Integrate the eXpected energy evolution*. Results. 2009

[74] GEIDL, Martin ; ANDERSSON, Göran: Operational and topological optimization of multi-carrier energy systems. In: *2005 International Conference on Future Power Systems*, 2005, 6 pp-6

[75] MEDJROUBI, Wided ; MÜLLER, Ulf Philipp ; SCHARF, Malte ; MATKE, Carsten ; KLEINHANS, David: *Open Data in Power Grid Modelling: New Approaches Towards Transparent Grid Models*. In: *Energy Reports* 3 (2017), S. 14–21

[76] LI, Zhigang ; WU, Wenchuan ; WANG, Jianhui ; ZHANG, Boming ; ZHENG, Taiyi: *Transmission-Constrained Unit Commitment Considering Combined Electricity and District Heating Networks*. In: *IEEE Transactions on Sustainable Energy* 7 (2016), Nr. 2, S. 480–492

[77] BAKKEN, B. H. ; HOLEN, A. T.: Energy service systems : Integrated planning case studies. In: *IEEE Power Engineering Society General Meeting, 2004*, 2004, S. 2068–2073

[78] ENERGYPEDIA (Hrsg.): *openmod intiative*. 2017

[79] PFENNINGER, Stefan ; PICKERING, Bryn: *Calliope: a multi-scale energy systems modelling framework*. In: *Journal of Open Source Software* 3 (2018), Nr. 29, S. 825

[80] HILPERT, S. ; KALDEMEYER, C. ; KRIEN, U. ; GÜNTHER, S. ; WINGENBACH, C. ; PLESSMANN, G.: *The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling*. In: *Energy Strategy Reviews* 22 (2018), S. 16–25. URL http://www.sciencedirect.com/science/article/pii/S2211467X18300609

[81] DORFNER, Johannes ; DORFNER, Magdalena ; SCHÖNLEBER, Konrad ; ZIPPERLE, Thomas ; HERZOG, Simon ; SIALA, Kais ; AKCA, Okan: *Tum-Ens/Urbs* : *V0.7.2* : Zenodo, 2017

[82] WALL, Göran: *Exergy tools*. In: *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 217 (2003), Nr. 2, S. 125–136

[83] SCIUBBA, Enrico ; BASTIANONI, Simone ; TIEZZI, Enzo: *Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy*. In: *Journal of Environmental Management* 86 (2008), Nr. 2, S. 372–382

[84] VALERO, A. ; LOZANO, M. A. ; SERRA, L. ; TORRES, C.: *Application of the exergetic cost theory to the CGAM problem*. In: *Energy* 19 (1994), Nr. 3, S. 365–381

[85] LOZANO, M. A. ; VALERO, A.: *Theory of the exergetic cost*. In: *Energy* 18 (1993), Nr. 9, S. 939–960

[86] FRATZSCHER, Wolfgang ; BRODJANSKIJ, Viktor ; MICHALEK, Klaus: *Exergie* : *Theorie und Anwendung* : Springer Verlag, 2013

[87] SZARGUT, Jan: *Towards a rational evaluation of steam prices*. In: *Gospodarka Cieptaa* 5 (1957), Nr. 3, S. 104–106

[88] SCIUBBA, Enrico: *Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems*. In: *Exergy, An International Journal* 1 (2001), Nr. 2, S. 68–84

[89] QIU, Zhifeng ; DECONINCK, Geert ; BELMANS, Ronnie: A literature survey of Optimal Power Flow problems in the electricity market context. In: *PES '09* : *IEEE/PES Power Systems Conference and Exposition, March 15-18, 2009, [Seattle, Washington*. [Piscataway, N.J.] : [IEEE], 2009, S. 1–6

[90] BELL, K. R. W. ; TLEIS, A. N. D.: Test system requirements for modelling future power systems. In: *IEEE PES General Meeting* : IEEE, 2010 - 2010, S. 1–8

[91] KIUREGHIAN, Armen Der ; DITLEVSEN, Ove: *Aleatory or epistemic?* : *Does it matter?* In: *Structural Safety* 31 (2009), Nr. 2, S. 105–112

[92] AIEN, Morteza ; HAJEBRAHIMI, Ali ; FOTUHI-FIRUZABAD, Mahmud: *A comprehensive review on uncertainty modeling techniques in power system studies*. In: *Renewable and Sustainable Energy Reviews* 57 (2016), S. 1077–1089

9 APPENDIX A: PEER REVIEWED PUBLICATIONS

Paper 1: Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges.

KRIECHBAUM, Lukas ; SCHEIBER, Gerhild ; KIENBERGER, Thomas; In: *Energy, Sustainability and Society* 8 (2018), Nr. 1, S. 244

I carried out the whole literature review (except for the modelling frameworks part), conceptualised the paper and wrote the manuscript.

Paper 2: Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation.

KRIECHBAUM, Lukas ; KIENBERGER, Thomas; In: *Energies* 13 (2020), Nr. 1, S. 182

I developed the methodology, created the case studies, conceptualized the paper, and wrote the manuscript.

Paper 3: Modelling Grid Constraints in a Multi-Energy 2 Municipal Energy System using Cumulative Exergy 3 Consumption Minimisation

KRIECHBAUM, Lukas ; GRADL, Philipp ; REICHENHAUSER, Romeo ; KIENBERGER, Thomas:. In: *Energies* 13 (2020), Nr. 1, S. 182

I developed the methodology, created the case studies, conceptualized the paper, and wrote the manuscript.

10 PAPER 1

Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges.

Kriechbaum *et al. Energy, Sustainability and Society* (2018) 8:35
https://doi.org/10.1186/s13705-018-0176-x

Energy, Sustainability and Society

REVIEW

Open Access

Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges

Lukas Kriechbaum*, Gerhild Scheiber and Thomas Kienberger

Abstract

Background: The transition to a sustainable future challenges the current energy grids with the integration of variable, distributed renewable energy sources. On a technical level, multi-energy systems may provide the necessary flexibility to minimise the gap between demand and supply. Suitable methods and tools are necessary to derive relevant results and to support a transition to renewable energy sources. While several, dedicated tools to model grids and infrastructure of single-energy carriers exist, there are no tools capable of modelling multi-energy systems in detail. Thus, this paper presents the necessary aspects to consider when modelling grid-based multi-energy systems, presents three open source frameworks for modelling grid-based energy systems and points out the major challenges.

Methodology: The current main aspects and challenges for modelling grid-based energy systems are derived from a literature review. Three open source multi-energy modelling frameworks (Calliope, oemof, urbs) are presented, and the extent to which they consider these aspects and how they tackle challenges is analysed.

Grid-based MES modelling: We identified five general energy system modelling aspects (modelling scope, model formulation, spatial coverage, time horizon, data) and three aspects specific to modelling energy grids (level of detail, spatial resolution, temporal resolution). While the specific aspects mainly influence the representation of the technical parts of the energy system and the computational effort, the general aspects primarily relate to the system boundaries and scope of the model. For the evaluation of the modelling results, we identified several assessment criteria, including economic, energetic, exergetic and reliability. Each of the studied open source modelling frameworks provides generic capabilities to model energy converters, and the electricity, gas and district heat networks. However, the general and specific aspects present respective challenges. Relating to the general aspects, complexity of model formulation increases when including additional boundary conditions. The accuracy of the results is also dependent on data quality. Temporal and spatial resolutions are the major specific challenges for modelling the energy infrastructure.

Conclusions: There is still a broad field of opportunities for researchers to contribute to grid-based energy system modelling. This encompasses especially the consideration of short- and long-term dynamics of renewable energy sources in planning models.

Keywords: Energy systems analysis, Energy assessment, Open source energy modelling frameworks

Background

Clean and sustainable energy supply is a societal challenge of the twenty-first century. Despite the world's primary energy supply rising from 255 to 571 EJ between 1973 and 2015, the share of energy produced from fossil fuels has not changed significantly and is currently still above 80% [1]. Different studies project a primary energy consumption between 770 and 1175 EJ in 2050 due to population and economic growth [2]. Over the upcoming decades, the primary energy supply from fossil fuels is expected to rise by approximately 1.5% per year [3]. Until now, the utilisation of fossil fuels accounts for 68% of the world's anthropogenic greenhouse gas emissions [4]. In order to mitigate global warming, mainly caused by anthropogenic green house gas emissions, the parties of the United Nations Framework Convention on Climate

*Correspondence: lukas.kriechbaum@unileoben.ac.at
Chair of Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef-Strasse 18, 8700, Leoben, Austria

Change reached an agreement on lowering carbon energy supply at the COP 21 in Paris [5]. The participating countries must adapt their energy policies to achieve the goals of the Paris agreement. Energy policy as a distinct field emerged with the occurrence of the first oil crisis [6]. Energy system models provide 'the integrating framework that assists energy policy and industrial decision makers' [7]. The main goal of energy system modelling was 'not to compute precise numbers but to gain insight into any complex system' [8]. Mathematical methods like linear programming developed for operations research in the Second World War [9, 10] were used to create models which allowed the formalisation of scattered knowledge about complex interactions in the energy sector and helped analysts to understand a sector that had become complex [11].

The history of energy system planning was primarily closed and proprietary, but market liberalisation and the need for greenhouse gas emissions reductions require changes in the transparency of modelling assumptions and methodologies [12]. Pfenninger et al. [12] present four reasons why data and models are not open: very often, *sensitive data* is used; sharing details and models creates an *unwanted exposure*, the effort to *publish and maintain* the model and *institutional and personal inertia*. However, transparency of the model, the datasets used and the communication of the assumptions made are all important points for the reproducibility and the acceptance of the results [13, 14].

The need for transparency and the challenge to integrate variable renewable energy sources (RES) [1] call for new types of models. These models must incorporate the rapid deployment and variability of wind and photovoltaic power loads as well as the growing importance of flexibility options like energy storage and grid expansion [15]. They must also consider high spatial, temporal and technological details to accurately assess and estimate the effects caused by such changes [12].

In this review article, we present a comprehensive overview of the current, grid-based multi-energy system (MES) modelling. The "Motivation" section is followed by the "Definitions and methodology" section—where we provide necessary descriptions of the review and derive our review approach. In the "Integrated grid-based MES modelling" section, we first present general MES modelling aspects as well as the specific grid-based MES modelling aspects. The modelling approaches for energy networks, storage and converters are outlined in the "Grid-based MES modelling approaches" section. This section is followed by the presentation of three open source modelling frameworks in the "MES open source modelling frameworks" section. Subsequently, in the "MES modelling challenges" section, we discuss current and possible future issues of MES modelling. The "Conclusions" section summarises and closes this review.

Motivation

Integrated energy system models try to create a representation of the various interactions between environment, resources, technology and investment, and economy and society (Fig. 1). Development of the first energy system models started in the 1970s. The Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA) first produced the MARKAL (MARket ALlocation) [16] modelling platform. The International Institute for Applied Systems Analysis (IIASA) developed its Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE [17, 18]). Both models were originally designed for bottom up optimisation of large-scale energy systems of countries or at an international level. Therefore, they require extreme simplifications such as country level aggregated values and seasonal or annual supply and demand balance [19]. Because all of the simplifications were accepted and well understood in energy systems consisting of base-load and fully dispatchable generators, such an *energy-based perspective* was sufficient for the desired purpose of such models. However, due to the temporal variability of RES, those tools may not fully capture the complexity of current and future energy systems. This leads to the necessity of a *power-based perspective* of future energy systems.

In this review, we focus on integrated, grid-based MES for three main reasons: (1) for a decarbonisation of the global energy system, fossil fuels must be substituted by renewable electricity [20], (2) the integration of fluctuating RES is especially a challenge for the electricity grid [21] and (3) an integrated MES approach supports a better utilisation of volatile RES and existing grid infrastructures [22].

The first two reasons address the implications of substituting fossil fuels for RES. For example, the shift from gasoline or diesel cars to electric cars powered by renewable energy [23]. Reason (3) considers the need to provide flexibility and virtual storage capacities[1] when integrating variable RES. This is to overcome the gap between fluctuating supply and demand.

As described in the introduction, most of the energy system models and modelling frameworks are opaque black or grey boxes. However, this has changed in recent years with the public release of many models and modelling frameworks [25]. Compared to proprietary models and modelling frameworks, in open source energy modelling, all stages of the process should be open and transparent (Fig. 2). According to [12], the main advantages of open source energy system models are (1) an improved quality of science due to increased transparency and reproducibility, (2) more effective and broader collaboration, (3)

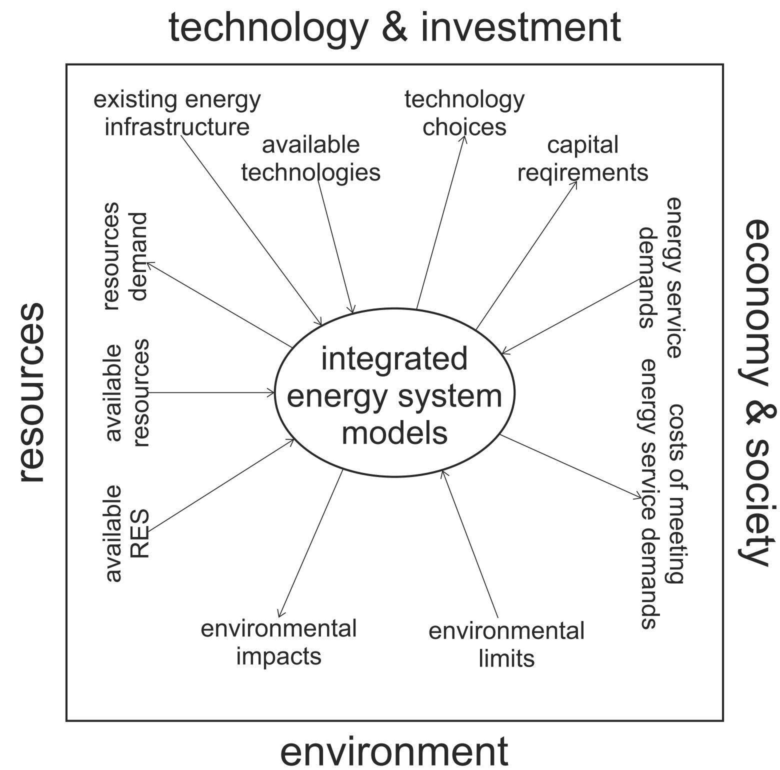

Fig. 1 Integrated energy systems modelling. Representation of the interactions between environment, resources, technology and investment, and economy and society in an integrated grid-based MES model. Adapted from [19]

increased productivity because of burden sharing and (4) a profound relevance to social debates.

Definitions and methodology

Different interpretations regarding the terminology and system boundaries in energy system modelling are available. Their use and interpretation within this paper is described in this section, together with the methodology of this review article.

Definitions

The system boundaries must be carefully selected in order to adequately assess the overall system. For MES, all energy carriers ranging from extraction to services must be included within the system boundaries. In this work, the definitions of an energy system and sector according to [27] are used. An *energy system* includes 'all steps in the chain—from primary energy resources to energy services'. The *energy sector* refers to 'the steps in the chain, from the extraction of primary energy resources to the delivery of final energy carriers for use in end-use technologies that produce energy services or goods'.

A consistent definition of *Multi-Energy-Systems* (MES) has currently not been found. In general, a MES approach requires holistic consideration of an energy system, covering the energy stages from the extraction and treatment (e.g. gas well, coal mine, sun) to the services (e.g. heating, illumination, transport), while also considering the different carriers (e.g. electricity, natural gas, oil, coal). In this paper, we focus on the grid-based energy carriers of the

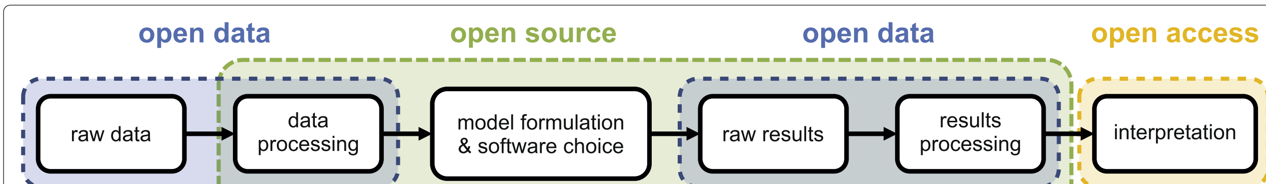

Fig. 2 Open source energy sytems modelling. Open access in all stages of the energey systems modelling process: open data, open source and open results. Taken from [26]

energy sector in the range from primary energy to final energy (marked by the dashed box in Fig. 3). Mancarella [28] points out four categories to characterise MES: spatial, multi-service, multi-fuel and network. While multi-service means that one energy source can supply energy services at the same time (e.g. a combined heat and power plant), multi-fuel means that different services can be provided by multiple primary energy carriers (e.g. domestic heat can be produced by a heat pump or a gas boiler). The spatial category describes the spatial resolution of a MES model, where common resolutions are buildings, cities and entire countries. Energy networks are required to overcome the spatial distance between consumers and producers and to enable the development of multi-energy technologies and their interactions. In addition to the four categories Mancarella consider, time resolution should also be considered in models integrating variable RES and energy storage. Therefore, when considering MES in our work, five categories are incorporated: spatial, time, network, multi-service and the multi-fuel.

The definitions of *model*, *model generator* and *framework* are taken from [29]. Models are simplified replicas of real world systems and may consist of several hard- or soft-linked sub-models. Model generators allow users to build models by the use of pre-defined units (e.g. a pre-defined set of equations represents a storage unit and converter). A modelling framework is a structured toolbox and may consist of sub-frameworks and model generators.

Methodology

The aim of this review is to give a comprehensive overview and to discuss the requirements of grid-based MES models. Additionally, selected open source modelling frameworks are presented and characterised. Our work draws on several recent reviews of MES modelling and the implied challenges (Table 1). Additional literature was consulted where necessary. The reviews can be grouped into five different fields: general MES modelling [19, 28, 30], modelling of urban MES [31, 32], categorisation of energy system models and frameworks [29, 33], evaluation of the challenges in energy system modelling [11] and the power flow modelling [34].

The review of Hall et al. [33] presents the prevalent usage and categorisation of energy system models in the UK. A qualitative evaluation method to categorise energy sytem modelling frameworks is proposed by Wiese et al.

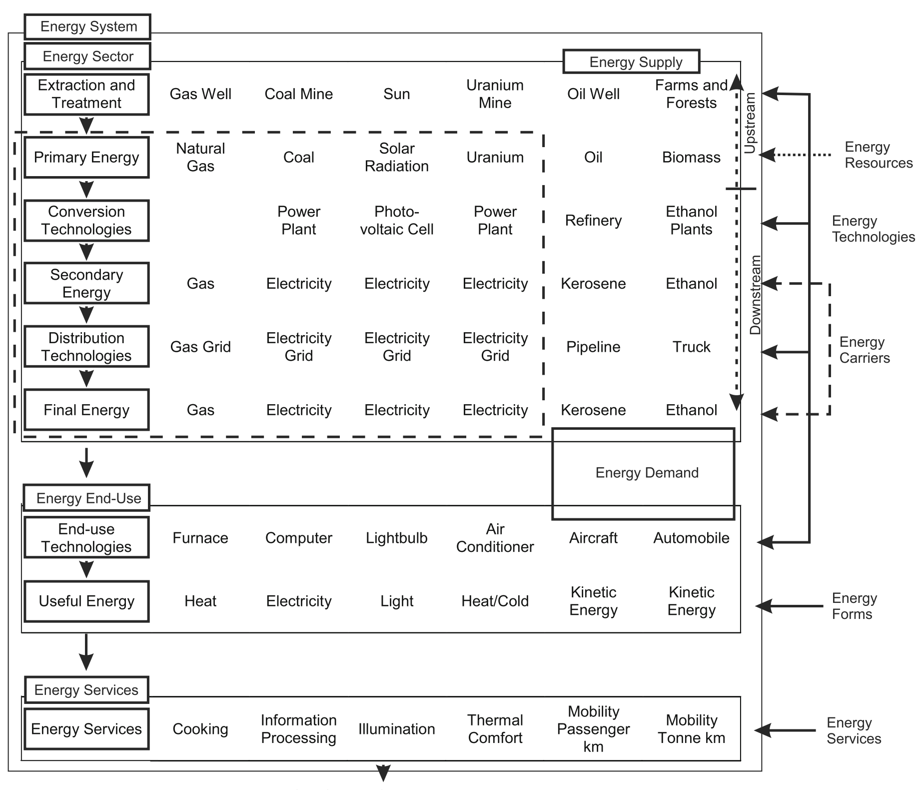

Fig. 3 Schematic of the energy system, energy sector, energy end-use and energy services. The energy sector includes the stages energy extraction and treatment, conversion, and distribution of final energy. The flow of the different energy carriers through the stages are illustrative examples and are not fixed. The system boundaries for this review are enclosed by the dashed box. Figure adapted from [27]

Table 1 Relevant literature on MES modelling and modelling challenges

Publication	Focus	Coverage
Keirstead et al. [31]	Urban energy system models: approaches and challenges	279 publications
Mancarella [28]	MES concepts and modelling	172 publications
Pfenninger et al. [11]	Challenges of energy systems modelling	130 publications
van Beuzekom et al. [32]	MES for urban sustainable development	78 publications
Mancarella et al. [19]	Integrated MES modelling	132 publications
Hall et al. [33]	Categorization of energy system models	163 publications
Syranidis et al. [34]	Electric power flow modelling	138 publications
Mohammadi et al. [30]	Energy hub modelling approach	153 publications
Wiese et al. [29]	Evaluation of energy system modelling frameworks	91 publications

[29]. Mohammadi et al. [30] analyse recent developments in the field of the energy hub, which is a generic and extensive MES approach (further details can be found in the "Energy hub" section). In his review, Mancarella [28] gives a broad overview on the currently available MES concepts, evaluation models and assessment techniques. In a later review Mancarella et al. [19] focus on the modelling of integrated MES. They present the requirements, opportunities and MES modelling applications ranging from optimal unit scheduling, optimal RES integration and optimal power flow between energy hubs.

Van Beuzekom et al. [32] identify suitable modelling tools and frameworks, whereas Keirstead et al. [31] identify and evaluate the influence of technology design, building design, urban climate, systems design, policy assessment, and land use and transportation modelling. A further two reviews [11, 29] look at the general challenges of recent energy system modelling. Only one review was found which focuses on modelling of control techniques and the modelling of electrical power flow across transmission networks [34], but nothing was found regarding the modelling of natural gas or district heating grids.

We used the literature review to determine the general aspects, modelling approaches and challenges for modelling MES as well as those specific to grid-based energy systems. For the evaluation of such energy systems, suitable assessment criteria are provided. Three selected open source MES modelling frameworks are assessed. Specifically, the review analyses each framework's modelling approach and the extent to which the necessary aspects are considered.

We identified five general aspects important to MES modelling as well as three grid-specific aspects (Table 2). In the following section, each of the aspects is presented in further detail and discussed. The two most common *modelling scopes* today are planning and operation. While planning models evaluate the long-term evolution of the energy system, operational models assess the operational soundness of scenarios. For planning models, the *time horizon* is especially important because it determines how far the model looks into the future. MES may range from a single building to districts, cities or whole countries. This is described in the *spatial coverage*. The mathematical *model formulation*, together with the programming technique, influences the possible level of detail and the necessary computational effort. For detailed models, *data* availability is essential, since it is often not known or is of bad quality. The *level of detail* describes how thoroughly the physical properties of the single components (e.g. part load efficiencies, power flow models) are considered within the model. The necessary aggregation and network representation are mainly affected by the *spatial resolution*. For the integration of variable RES, the *temporal resolution* is important and determines to which extent short- and long-term dynamics can be considered.

The MES modelling approaches consist of full and hybrid concepts. While the full approaches consider all available energy carriers, the hybrid approaches consider only some. The different energy and power flow representations in electricity, gas and district heat networks provide various degrees of detail. They range from simple network flow models to more detailed power flow representations like DC or AC load flow.

Based on the general and specific modelling aspects, three open source modelling frameworks which are suited to model grid-based MES are evaluated according to the modelling aspects and approaches stated out above. The major requirements for such tools are the possibility to model multiple energy carriers, a temporal resolution to

Table 2 General and specific grid-based MES modelling aspects

General aspects	Specific aspects
Modelling scope	Level of detail
Model formulation	Spatial resolution
Spatial coverage	Temporal resolution
Time horizon	
Data	

model the short and long term dynamics of RES, a spatial resolution to model energy or power flows and suitable network or power flow representations.

Also compiled from the literature review are the modelling challenges. Data availability, data quality and increased model complexity (e.g. because of modelling data uncertainty or human behaviour) are all challenges affecting the general modelling aspects. The specific challenges refer to the representation of time and space in the model.

MES modelling aspects and assessment

According to Box and Draper, 'essentially, all models are wrong but some are useful' [35]. To receive a useful result from a model, it is crucial to model the values which are relevant to the problem and not those which lend themselves to modelling [11]. Therefore, in the next sections, we discuss several important aspects for MES modelling, from general to specific grid-based modelling aspects to the assessment of the results.

General aspects

Top-down (or macroeconomic) and bottom-up (techno-economic) are the currently most typical energy system modelling approaches (Table 3). Models using top-down approaches try to provide a holistic perspective of the economy (this includes economic growth, employment, trade, etc.), but only consider the energy sector in a simplified and aggregated manner. In comparison, bottom-up models incorporate more technological detail and use an economically driven approach for evaluating investigated technologies. This allows them to provide more detailed outlooks on future supply and demand and possible technology utilisation. The high technological detail requires extensive data. Many assumptions have to be made regarding technology diffusion, investments and operating cost [36].

Since modelling grid-based energy systems requires a high level of technological detail we further focus only on bottom up modelling approaches in this work.

Modelling scope

Planning models are used to investigate the long term evolution of energy systems. They consider investment decisions and account for a change in future parameters like fossil fuel availability, renewable resources, technology prices, technology diffusion and future learning. These parameters are input variables for energy systems models, and must be chosen carefully to avoid creating biased results [29]. Typical energy planning models are MARKAL/TIMES and MESSAGE. Planning models typically use an energy-based perspective because they work with highly aggregated data (e.g. annual demand and supply values). Operational models examine the operational feasibility of a scenario and since the energy demand must be met at any time of the investigated period, a power-based perspective is necessary. This requires consideration of the short and long term dynamics of supply and demand, as well as technological, regulatory, economic and social constraints [15]. Typical operational models are PLEXOS, GTmax and EnergyPLAN.

Time horizon

The time horizon is closely connected to the modelling scope. While common time horizons for planning model are 30 to 50 years, typical investigation periods for operational models range from a day to a year [32, 37].

Spatial coverage

The spatial coverage may range from a local, single building to districts and countries. It has a vast impact on the suitable programming techniques, the possible level of detail [38], and the possible time horizons and time-steps [37]. A classification of current MES models according to their spatial dimension and level of detail shows that models which cover a spatial dimension that is greater than multiple buildings usually use rather simple, highly aggregated modelling approaches with constant conversion efficiencies between energy carriers (Fig. 4, see also sections "Programming techniques" and 'Level of detail') [38].

Model formulation

The most common modelling approaches for bottom-up models are simulation [2], optimisation [3] and partial-equilibrium [4] models [36]. Newer approaches include agent-based-modelling and co-simulation [39]. While simulation is descriptive, meaning it forecasts how the energy system might evolve, optimisation is normative—its primary aim being to provide scenarios of how the energy system could evolve [11].

Describing the physical world (e.g. energy generation, distribution, infrastructure and their components) usually results in continuous models with linear and non-linear behaviour [40]. To create mathematically tractable models for integrated simulation or optimisation problems, the equations must be brought to a common problem formulation. The ones most commonly used are linear

Table 3 Energy systems modelling approaches [36]

Top-down	Bottom-up
Input-output models	Simulation models
Econometric models	Optimisation models
Computable general equilibrium models	Partial equilibrium models
System dynamics models	Multi-agent models

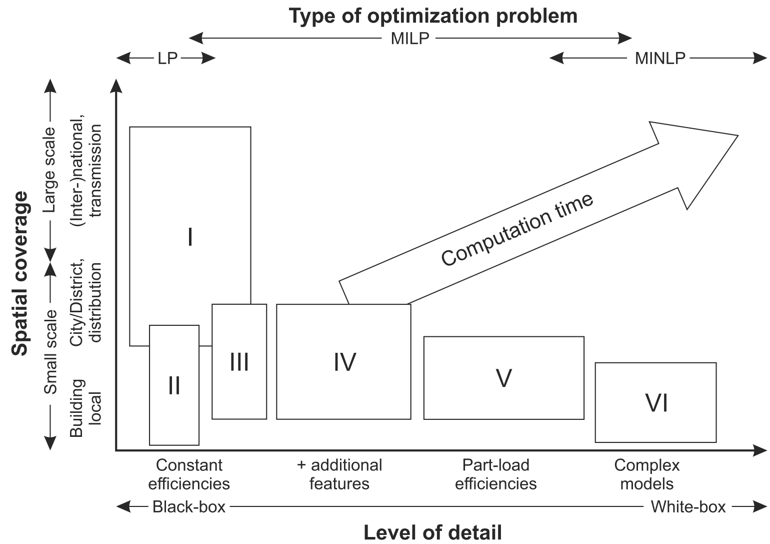

Fig. 4 Spatial coverage, model level of detail and typical optimisation problem formulation. Classification of existing MES models according to their level of detail and spatial resolution. I: large-scale grid studies relying on simplified models, II: simple tools for quick assessments of small-scale energy systems, III: building and city district energy system design studies with simplified models, IV: on-site energy system studies with additional features, V: mixed-integer linear programming with part-load efficiencies and VI: mixed-integer non-linear programming with complex models. Adapted from [38]

programming (LP), mixed-integer linear programming (MILP), mixed integer non-linear programming (MINLP) and dynamic programming (DP) [13]. In LP, all relationships are expressed in fully linearised terms that makes it an eas-to-use technique which delivers quick results [41]. However, the constant coefficients are also one of its main disadvantages, leading to deviations if describing non-linear phenomena. Almost all optimisation models for energy planning and technology-related, long-term energy research are LP models [37]. MILP is an extension of LP as it allows a greater detail in formulating technical properties and relations. It adds decision variables and non-convex relations which allow, for example, to model an on/off mode for individual units [42]. MINLP can also take into account non-linear objective functions and constraints meaning that it most closely approximates real world systems [43]. However, this adds a layer of complexity since the identification of the global optimum among the local optima in non-linear problems requires greater computational effort [44]. Because of the computationally costly solution process, MILP and MINLP models are usually applied only on small scale energy systems (Fig. 4, e.g. for dispatch modelling of combined heat and power plants [42] or thermal energy storage utilisation in an energy system with high shares of distributed energy sources [45]). DP is a method to find the optimum growth path. The problem is divided into several simple sub-problems for which the optimum solution is calculated and then combined to a global solution [41]. This method was applied for example on distribution system expansion planning [46] or the optimal operation of a distribution network with dispersed generation units [47].

Data

The vast amount of data required for detailed bottom-up models causes challenges for the modellers. The necessary data is often not available because it is either not measured (high resolution load profiles of gas and electricity), is commercially confidential [48], relates to the future and is highly uncertain [19], or is of doubtful quality. Even though several methods exist to deal with this issue (probabilistic approaches, possibilistic approaches, interval programming, robust optimisation, etc. [49]), the majority of energy system models uses a deterministic logic (e.g. MARKAL, MESSAGE, etc.) and do not take into account any uncertainties. Probabilistic approaches use probability density functions for the input variables [9], for example the Weibull distribution of wind speed patterns [50]. In comparison, possibilistic approaches, also called fuzzy approaches, use membership functions to describe uncertainties [51]. Interval linear programming can deal with uncertainties in the system constraints and the objective function, as the lower and upper boundaries are specified. However, it cannot handle distribution functions [52].

Specific modelling aspects

While planning models have a long time horizon and coarse temporal and spatial resolutions, operational models have a significantly shorter time horizon and finer temporal and spatial resolutions. The variable and distributed nature of RES, the inclusion of energy storage, and the restricted transport capacities of transmission lines demands that finer temporal and spatial resolutions be used [11]. This calls for an increased level of detail which has an influence on the mathematical tractability and computational effort (Fig. 4). The different energy vectors and the technical infrastructure in a MES may require particular levels of detail, temporal and spatial resolutions [19]. These topics have recently been subject to many reviews, [53–57] evaluated the different levels of technical detail, [15, 53, 54, 58–61] focus on the temporal resolution and [62, 63] on the spatial details.

Level of detail

The different levels of detail can be divided into three categories: black-box, grey-box and white-box representations [64]. Black-box models are highly aggregated, data-based input-output models without a representation of the underlying physical principles [65]. Therefore, they lead to straightforward and easy-to-solve models. However, it should be ensured that they are appropriate and accurate enough for the relevant problem [66]. White-box models offer higher degrees of detail and are based on physical principles to calculate load flows and conversion efficiencies [65]. This also leads to increased modelling effort and the mathematical tractability of the model may cause issues [66]. Grey-box models use simplified physical representations, and their aggregation level and degree of detail is in between that of a white-box model and a black-box model [67] Almost all tools used for nationwide energy forecasts (e.g MARKAL/TIMES, MESSAGE, etc.) use grey-box or black-box approaches. As shown in Fig. 4, complex white box models have limited spatial coverage, there is no known model which features both.

Spatial resolution

MES models should consider spatial dimensions because energy supply and demand often occur in different locations. To connect demand with supply, energy transfer infrastructure is necessary [19]. The smallest known common entities in MES modelling are houses and residential buildings. In several papers, MES houses were addressed. Some examples include the high resolution modelling of residential demand [68] or the optimum integration of MES devices into buildings at design stage [69]. MES of the next resolution size—district or city—are the subject of intense research and many publications. In [70], integrated green- and brownfield MES approaches are used to determine the optimum solution for a district's future energy system. Another publication [22] deals with the exergetic optimisation of a city's grid-based energy system. Studies with a higher spatial coverage (e.g. [71, 72]) usually do not account for system operation and infrastructure details [19].

Aggregation of data is crucial for modelling MES. On the one hand, to make the problem computationally tractable and, on the other hand, to account for unavailable or unmeasured data, different spatial and temporal resolutions may lead to deviating results. For district heating in the UK, [73] used a spatially explicit model to model future district heat scenarios and [74] determined that different spatial resolutions provide different results for the optimum heat supply strategies. For electrical networks, bus-aggregation methods are used for network reductions [75, 76]. Such simplified networks are further used to determine the effects of aggregating electric loads in the USA [77] and Europe [76].

Temporal resolution

Using time-aggregated data, for example averaged hourly values, can lead to deviations in the results. For example, [78] showed that the design capacity of a micro combined heat and power plant varied by half between analysis using 5-min and 1-h time-steps. The necessary temporal and spatial scales for grid planning and operation as well as the resolutions of current MES tools are shown in Fig. 5. When modelling, it is assumed that fast phenomena have reached equilibrium at the end of a time-step. This is especially challenging when modelling MES as they cover a wide range of time scales, including microseconds in electric system operations, hours for gas transport in transmission lines and months in the case of seasonal influences of RES [19]. A possible solution to this problem is to interlink long-term energy system models with short term electricity system models. However, while the information flow from long-term models to short-term models works quite well, the reverse seems to be more challenging [55]. A major challenge in MES modelling is to select a proper temporal resolution to fit the scope. The shares of RES which can be integrated might be over- or under-estimated if an unsuitable resolution is chosen [15], for example [32] suggests a 15-min interval.

Assessment criteria

Choosing the appropriate assessment criterion and performance indicators is critical in the evaluation of MES. The most common criteria are economic, environmental or technical (energetic or exergetic). Qualitative and quantitative criteria exist, but only quantitative criteria can be used for the formulation of objective functions. The assessment and performance indicators can derive from an absolute or relative value, and a single- or multi-objective approach [28]. Other criteria like sustainability, resilience or socio-ecological effects are not considered in this section.

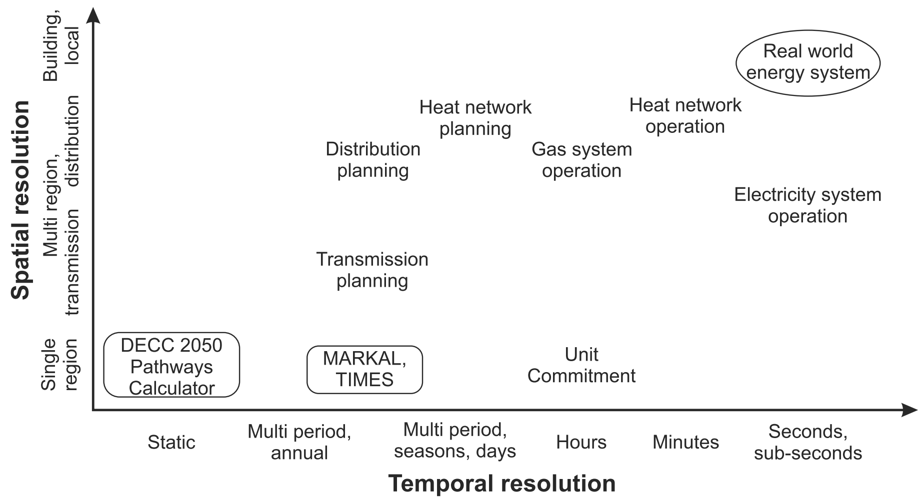

Fig. 5 Spatial and temporal scales in MES. The different spatial and temporal scales required for MES planning and operation and current MES model resolutions. Adapted from [19]

An *Economic Assessment* is the most widely used evaluation criterion. It can be applied anywhere from planning to the operational stage. The main premise is the minimisation of the total cost or the maximisation of profits. For planning purposes, the discounted cash flow or the net present value theory are usually used. At the operational stage, the analysis of costs and revenues caused by system operation is the typical approach.

An *Energetic Assessment* is the comparison of energy output to energy input, also called first law efficiency or energy efficiency. This can be conducted for individual components or whole systems during a particular operating state or over a certain period of time. Energy efficiency must always be compared to a reference case. An example of a relative indicator is when comparing energy savings by cogeneration to separate production [79].

An *Exergetic Assessment* considers the first and the second law of thermodynamics. Exergy describes the maximum share of energy that can be converted to useful technical work. While energy can be neither produced nor destroyed, it is the exergy that is consumed to provide a certain service. Therefore, exergy is a suitable common basis when comparing different energy carriers in a MES. Exergy analysis allows the evaluation of cascading energy usage and is a powerful tool for identifying causes, locations and magnitudes of primary energy losses [80].

An *Environmental Assessment* is an important criterion in the field of energy policy development. It covers the wide range of impacts of MES on the environment, like greenhouse gas emissions, air pollutants, influence on biodiversity and groundwater resources. In general it can be distinguished between local impacts, for example particulate matter and NO_x-emissions, and global impacts, such as greenhouse gases and chlorofluorocarbons. In this work, the environmental assessment focuses on the CO_2-emissions related to energy production.

The *Reliability Assessment* rates the ability of energy systems to provide an adequate supply. The main aim of the reliability assessment is to identify the weak and critical parts of the energy infrastructure, such as the outage rates of generating units, the failure rates of overhead lines and operational decisions. All those are predicted future events which cannot be estimated precisely and therefore have to be assessed probabilistically. Typical key performance indicators are *loss of load probability* (LOLP), *loss of load expectation* (LOLE), *expected energy not served* (EENS) and *loss of energy expectation* (LOEE) [81].

Grid-based MES modelling approaches

In addition to supply and demand, grid-based MES models must consider the energy flows in the networks, energy storage and the energy conversion between networks. Two approaches are used to model such systems: the integrated approach and model linkage or co-simulation. In the integrated approach, all components (networks, converters, storage) are modelled within the same framework. Co-simulation or model linkage means that several or all components have their own dedicated model, which are coupled by a superior tool. For the coupling tool, the sub-systems are black boxes.

Energy network modelling approaches

Energy transmission via networks can be modelled in various levels of detail. Geidl [82] suggests a classification into network (black-box models) and power flow (grey- or white-box models) models. Type I network flow models feature energy flows that transmit energy without losses. Conversely, in type II network flow models, losses are incorporated as a function of the corresponding flow. Power flow models are the most accurate and based on conservation of flow and on conservation laws, but also include non-linearities.

While the network flow models are relatively simple and the same for each of the three most common energy networks (electricity, gas and district heat), the power flow models are more complicated. Physical laws such as the relation between electric voltage and current, or hydraulic pressure and flow, are used to determine the load flows. Since these physical relations are specific for the individual energy carriers, no general model for all energy carriers is available [82]. For each network type there are dedicated static load flow calculation tools which are based on physical laws, for example NEPLAN [5], PSS SINCAL [6] or DIgSILENT PowerFactory [7]. As well as modelling electricity networks, the first two tools can also model district heat and gas networks, however, it is not possible to interconnect each energy carrier.

Electric networks

There are two different approaches to model electrical power flow, the linear DC model and the more realistic AC model [83]. For the DC model, Kirchhoff's law is used to determine the active power flows which depend on the maximum power capacity and the resistance of the power lines [84]. Very often, linear DC power flow is used in operational electricity system models to decrease the complexity and calculation time for the non-linear optimal power flow problem [85]. For example, DC load flow models were used in two recent studies on the German electricity grid. One [86] investigated the necessary long term grid expansion due to the RES integration, the other was used to determine the optimal placing of storage power plants in 2020 [87]. DC load flow network representation was also used for an integrated day-ahead electricity market model in Turkey [88]. Several papers address the accuracy of DC load flow formulations [89] or compare results gained by AC and DC formulations [85, 90, 91].

As AC load flow representations also account for active and reactive power flows, data regarding capacitive and inductive behaviour of the transmission lines is required. However, this increased detail adds to the complexity of the model and results in longer calculation times [84]. Solving large-scale electricity systems with an AC power flow representation is still a challenge because for some operation states, standard methods like Newton-Raphson or optimal power flow do not deliver any results [85] and prevent full AC power flow models from being widely adopted in real time operation [92]. All of the above mentioned load flow calculation tools are capable of AC power flow calculations. Geidl and Andersson [93] used an AC load flow representation to determine the optimum power flow in an interconnected system of energy hubs. Other applications are the determination of the optimal load flow in the distribution grid [94].

Pipeline networks

Power flow models for pipeline networks must consider pressure losses and, in the case of district heat grids, must also consider heat losses and the temperatures of the feed and return flows. The tools described above, NEPLAN and PSS SINCAL, can solve the non-linear power flow equations, for example by using the Newton-Raphson algorithm. The non-linear dependency between flow and pressure loss is a challenge in case of integrated MES simulation, because it requires either linearisation or a non-linear problem formulation. Several works have dealt with optimal power flow modelling in MES: for pipeline networks, they either linearised the equations [95] or used non-linear models [93, 96]. In practical modelling, generally static equations are used. This means that fast phenomena are negligible and have reached equilibrium before the end of the time-step [19]. In the case of fine time resolutions and large-scale pipeline networks, equilibrium might not be reached at the end of a time-step meaning full transient equations are necessary [97] to consider the changes in the linepack [8] [19]. The same applies if modelling storage that is intrinsically available in existing infrastructure, for example if using the slower dynamics as flexibility option for the power grid [99].

Converter and storage modelling approaches

There are several converter and storage modelling concepts with various levels of detail. The most generic one is the *energy hub* concept [100] which was specifically developed for describing the power flows in interconnected, grid-based MES. In his review, Mancarella [28] also includes the *microgrid* [101] and *virtual power plant* [102] modelling concepts, which were originally designed for power grid modelling, in the MES modelling concepts. A more recent concept is the *power node* modelling concept [103]—originally designed to model energy storage in electrical power systems. Whereas the energy hub is a full multi-energy modelling concept, the others primarily target the electricity system and only consider some multi-energy aspects, but do offer a higher degree of detail.

Energy hub

The *energy hub* concept is a generic approach for steady state modelling and optimisation of future interconnected multi-energy networks [82, 93]. The energy hubs serve as interfaces between different energy infrastructures (e.g. connecting the natural gas network to the electricity and heat grid using a co-generation plant) and network participants (consumers, producers). The basic elements of an energy hub are converters, energy storage, and input and output connections (Fig. 6). A converter is described by the energy efficiency $\eta_{\alpha,\beta}$ between input of energy carrier α and output of energy carrier β and can have multiple power inputs P^{in} and outputs P^{out}. A hub can consist of a single device or a combination of multiple converters and has dedicated inputs and outputs. The general formulation of energy conversion for a multi-input and multi-output hub is analogous to a single converter and can be stated as followed [104]:

$$\begin{pmatrix} P_\alpha^{out} \\ P_\beta^{out} \\ \vdots \\ P_\omega^{out} \end{pmatrix} = \begin{pmatrix} \eta_{\alpha,\alpha} & \eta_{\beta,\alpha} & \cdots & \eta_{\omega,\alpha} \\ \eta_{\alpha,\beta} & \eta_{\beta,\beta} & \cdots & \eta_{\omega,\beta} \\ \vdots & \vdots & \ddots & \vdots \\ \eta_{\alpha,\omega} & \eta_{\beta,\omega} & \cdots & \eta_{\omega,\omega} \end{pmatrix} \begin{pmatrix} P_\alpha^{in} \\ P_\beta^{in} \\ \vdots \\ P_\omega^{in} \end{pmatrix} \tag{1}$$

Energy systems of various scales and resolutions can be represented by a set of interconnected energy hubs. The energy transmission between the hubs can be represented by network or power flow models. The original approach uses a black-box modelling approach with constant conversion efficiencies for converters.

The majority of energy hub applications use an integrated modelling approach. Although the energy hub concept was originally developed for greenfield design studies [105], it has been used for several other purposes. In addition to optimal dispatch [104], optimal power flow modelling in the networks [93] and topological optimisation [106], energy hub models were also used for reliability considerations [107] and exergetic optimisation [108]. A decent collection of published research on the energy hub can be found in [30].

Hybrid concepts

A *micro-grid* is a distribution system with interconnected loads and distributed energy sources (PV, wind, storage, etc.) which is controlled in a coordinated way, allowing it to operate in parallel with the grid or in island mode [109]. Micro-grids can be MES, if the loads and supplies of other forms of energy are included in their control strategy as well. Examples are the integration of co- and tri-generation as well as electrical heat pumps. A tool for efficient design and operation of polygeneration micro-grids was presented by [110, 111]. The application of a MES micro-grid was shown at the University of Genua [112].

A *virtual power plant* (VPP) is a flexible representation of a portfolio of distributed energy resources. They are aggregated and coordinated in a way so that they act as a single power plant [113]. Currently, small power generation facilities like battery storage and distributed energy resources are generally prohibited from the electricity spot market [114]. Virtual power plants can help overcome these barriers and meet the requirements for participation in the European Energy Exchange spot market [115] and the control energy tenders [116, 117]. The application of VPP in MES concentrates on providing system flexibility, for example by including thermal storage in a cluster of CHP plants [118] or by using aggregated resources like heat pumps, electric vehicles and electrolysers in replace of the spinning reserve [119]. For example, a VPP model is used to evaluate the feasibility of balancing the power in a renewables only power system using CHP, heat pumps and thermal storage [120].

The *Power Nodes* modelling concept is based on a Multilevel Flow modelling approach, which is usually used to model industrial processes on several interconnected levels [121]. A power node represents a generic storage which is inserted in between the grid and the supply and demand processes. This adds a new degree of freedom to balance the power grid and works in tandem with controllable loads by offering inherent storage capacity.

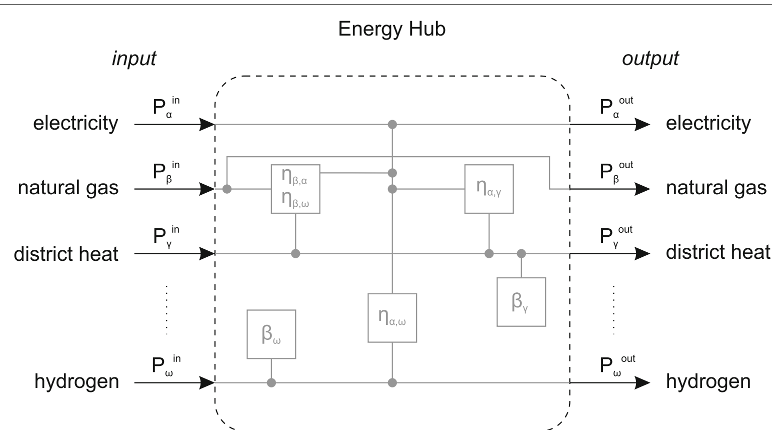

Fig. 6 Example of an energy hub that contains converters ($\eta_{\alpha,\beta}$) and storage (β_α). Power from the input is converted in order to meet the load. $\alpha, \beta, \ldots, \omega$ are the different energy carriers. Adapted from [104]

In order to provide a conceptual model for energy storage and different levels of controllability of power system units the power node approach aims to 'introduce a model decomposition for operation functions in different planning stages and operation time-scales' [122]. A multi-stage formulation is used to provide equations for day-ahead and intra-day rescheduling as well as real-time operation. Although the power node modelling concept is mainly designed solely for electricity grid simulations, it may also be used in a MES context when considering power-to-heat applications. In a case study, a power grid with intermittent electricity supply, thermal load and thermal energy storage was investigated [103, 122, 123].

MES open source modelling frameworks

While in earlier times, models designed for urban or utility energy systems were not commercially available [124], the situation has changed and today there are several accessible MES modelling concepts and open source modelling frameworks. For our review, a collection of 29 open source energy modelling tools was established from [25, 125, 126]. The complete collection, including information regarding the properties of the tools (e.g. programming language, available energy sectors, time resolution, energy grids), can be found in Additional file 1. Sixteen of these tools support modelling energy grids, and only seven of those allow the modelling of more than a single energy carrier. Balmorel [127], ficus [128] and PyPSA [129] focus on modelling electricity and heat supply. TransiEnt [130] is a Dymola library for modelling the transient behaviour of electricity, gas and district heat networks. Calliope [131], oemof [132] and urbs [133] are the most generic and flexible modelling frameworks as they support modelling user-defined energy sectors and grids. They also allow user-defined time-resolutions and horizons. Therefore we selected them for a further evaluation according to the modelling aspects and approaches stated above. A short description of each framework is provided followed by a comparison.

Calliope

Calliope is a framework used to model MES, developed by the universities ETH Zürich and University of Cambridge. The model is written in Python and has a clear separation of framework (code) and model (data). The focus is set on spatial and temporal explicitness, openness, transparency and the ability to compute and compare a large number of scenarios [11].

oemof

oemof is a 'modular open source framework to model energy supply systems' developed by the Reiner Lemoine Institut and the Center for Sustainable Energy Systems at Flensburg University of Applied Sciences. It is a collaborative modelling approach that is still under development. The modular structure offers the ability to adapt to the desired scope, making it flexible in time resolution and allows for the connection of multiple regions and energy sectors. It provides a rich set of tools to construct energy supply system models in high temporal and spatial resolution. The object-oriented implementation of the framework allows users to address the uncertainties of highly integrated future energy systems [134].

urbs

urbs is an energy modelling framework developed by the Technical University of Munich. It is a linear programming optimisation model built for capacity expansion planning and unit commitment for distributed energy systems. It is suitable for MES with a focus on optimising storage size and use. The optimisation objective is to minimise the cost of the energy system while satisfying the given demand [133].

Framework comparison

The general and specific characteristics of the modelling frameworks are summarised in Table 4. All of the modelling frameworks are based on the energy hub concept and cover the electricity, heat and gas sector. *oemof* stands out with the option to include the transport sector. The basic features included are renewable energy sources, converters (including co- and tri-generation), consumers, storage and grids for electricity, heat and gas. Type II network flow models are used to describe the energy transmission between multiple regions. Since all frameworks have operational and planning modes incorporated, they support high time resolutions and long term investigation periods. Using a deterministic optimisation model formulation, all frameworks accept linear equations. *oemof* and *Calliope* also accept binary variables. This only allows a basic level of detail but high spatial coverage.

The main objective of all frameworks is to minimise costs for a given scenario. As well as economic constraints, *urbs* also offers the opportunity to include CO_2 emissions as an auxiliary constraint. The economic analysis of *urbs* is especially advanced as it includes a number of economic variables outside of the fixed and variable standard costs. It allows the user to explore investment costs, start-up cost, time variable buy and sell prices for commodities and an annuity factor formula for a given depreciation duration and interest rate. Even though the basic functions of the tools are quite similar, they also have some unique features. *Calliope* and *urbs* support multi-scenario evaluation and *urbs* also provides demand response, while *oemof* offers the implementation of minimum up- and down-times for converters.

The source codes for all the frameworks are hosted on *github*[9]. The number of commits[10] made on these projects

Table 4 General and specific characteristics and features of the modelling frameworks

	Calliope	*oemof*	*urbs*
Modelling scope	Operational, planning	Operational, planning	Operational, planning
Model formulation	Linear	Linear and mixed integer	Linear
Spatial coverage	Local to countries	Local to countries	Local to countries
Time horizon	Short and long	Short and long	Short and long
Assessment criteria	Economic	Economic	Economic, with environmental auxiliary constraints
MES approach	Energy hub	Energy hub	Energy hub
Energy sectoral coverage	Electricity, gas, heat	Electricity, gas, heat, transport	Electricity, gas, heat
Spatial resolution	Single- and multi-region	Single- and multi-region	Single- and multi-region
Time resolution	Low and high	Low and high	Low and high
Load flows	Network flow type II	Network flow type II	Network flow type II
Unique features	Ramp rates, multi-scenario	Ramp rates for storage, up- and down times	Demand response, multi-scenario

indicates that all projects continue to have active online communities who are further developing the codes and correcting errors. Road maps and feature lists show the path and schedule for future developments and releases. Issues and bug reports posted on github are usually answered and fixed by the developer community within a reasonable time.

Appropriate documentations help to support new users with understanding the structure and functions of the frameworks. Compared to the other frameworks, *urbs* has broader ranging application possibilities which are supported by more extensively and detailed documentation. The well-structured source code of each framework is straightforward and of high quality. However, *urbs* stands out because its in-code documentation includes more details and additional information.

Even though *urbs* has the most extensive documentation, the broad functionality and sophisticated economic assessment make it time consuming to change the code. A considerable advantage of *oemof* is the clear and modular structure of the code which allows it to be easily adapted. In comparison to *oemof*, *Calliope* does not have such clear and strict separation between the model description, simulation and optimisation.

MES modelling challenges

Energy system modelling is influenced by various sectors and fields (see Fig. 1 and Table 5). As well as detailing energy infrastructure components and technology, energy system models must also account for the stochastic nature of RES and the behaviour of consumers and market stakeholders.

General aspects

The main challenge when modelling an energy system is to accurately model the desired problem, and to select the proper influencing factors and boundary conditions. It is important to model the factors that are relevant to the problem instead of prioritising factors that may be easier to use [11]. While energy system models are often implemented for technological and economic effects, they are rarely used to investigate the effects of aspects such as human behaviour, indirect costs, socio-political or non-financial barriers for technology [11].

Energy systems typically consist of the four interconnected fields listed in Table 5. On the path to a future energy system based on distributed RES, the number of interconnections between the individual energy carriers will need to increase. This adds to the complexity of the system and increases the overheads for maintenance [135, 136].

Model formulation

While there are several specialised and dedicated tools for modelling the individual segments of the energy system in various detail, there is no known transdisciplinary tool or method that combines all four fields stated in Table 5 in high detail. The more convoluted and interconnected a system becomes, the more difficult it is to solve the arising mathematical problem. Already when only modelling components and grids of a MES using the energy hub concept, the synthetic matrix representation leads to a model formulation that is intrinsically nonlinear due to the multiplication of decision variables [28]. Optimisation problems with non-linear constraints require additional optimality conditions (Karush-Kuhn-Tucker conditions) to find a globally optimal solution [82]. This makes the mathematical problem more difficult to solve. Another approach is to decompose the energy flows to obtain linear models [95]. However, this might lead to large errors because power flow equations for electricity and hydraulic networks are non-linear.

Table 5 Segments and modelling approaches for components of future energy systems [40]

Field	Modelling approach	Components
Physical world	Continuous models	Energy infrastructure and its components: generation, transport, distribution, consumption
Information Technology	Discrete models	Controllers, communication infrastructure, software
Roles and individual behaviour	Game theory models	Market players
Aggregated and stochastic elements	Statistical models	Weather, macro-view on consumers, aggregated behaviour of many individual elements

Including control systems in a MES model requires variable-structure, dynamic models [40]. Consumer behaviour and stochastic elements (Table 5) have rarely been included in energy system modelling to date. However, these factors are expected to be important in future applications despite adding many layers of complexity to the models. For example, in the UK, there are very few low carbon emission energy scenarios which also take into account social or political aspects [137]. The estimation of future energy demand and the required energy infrastructure can have significant influence on the future of energy supply [11]. In order to achieve a low-carbon emission future, energy demand must, in addition to energy supply, be addressed and managed [20, 138]. Furthermore, the public acceptance of renewable energy installations like rooftop solar panels in cities, on- and off-shore wind power plants, or new grid lines plays an important role for future energy systems. Overall, considering all four fields requires several different modelling methodologies, techniques and logics. This results in large stochastic hybrid models [40].

Data

Generally, there are two types of uncertainty: epistemic and aleatory [139]. An uncertainty is epistemic if the modeller thinks it can be reduced by better data and models, otherwise it is aleatory. There is no way to address epistemic uncertainties except for better models and data, but there are formal methods for dealing with aleatory uncertainties—an example is the Monte Carlo method. The Monte Carlo method, or similar approaches to determine uncertainty, examine the changes of a model's inputs and outputs by varying input data several times. The benefit of these methods is that they can be used in combination with existing deterministic models.

Stochastic models, for example, are designed to deal with uncertainties by handling a random input and producing a randomly distributed outcome. This means that distributions are fed into the model instead of deterministic parameters [11, 31]. Ideally, input data and parameters should be assigned with deviation ranges. However, the necessary input information might not always be of sufficient quality. Alternatively, it may be unavailable, or may only be available on an aggregated level because of data protection law limitations. If this is the case, then it must be adjusted or downscaled to the desired boundaries - for example from a national to a district level on a per-capita basis. Very often in these cases the uncertainty is difficult or impossible to determine. Unfortunately, the majority of studies do not describe the methods on how they dealt with the uncertainties related to their input data [31].

Specific aspects

The distributed nature and the necessary power-based perspective of RES mean that the modelling of time and space is crucial for accurate and robust results of MES models. Because it is very difficult to acquire sufficiently fine resolution data for RES, it is unlikely that traditional optimisation models (which use an energy based perspective) can fully represent the resolution challenges [11].

Time and space

Energy is not always supplied when and where it is required. This imbalance may be compensated for either spatially by the grid, or held by storage to be discharged at a later time. However, models with a high degree of spatial and temporal detail may require too much computational effort to be solved in an acceptable timeframe. Although a coarse resolution requires less computational effort, it can lead to inaccurate results. This is due its averaging character that may filter out the extreme points when designing the system [59]. Hayt et al. [58] determined in their work that models that do not consider the full variability of supply and demand can overestimate the share of demand met by renewable energies. There are three general approaches to address the variability of RES [11]: (1) capacity factors or load duration curves, (2) time slices of representative days or seasons and (3) real time series of RES production potential. Large-scale energy optimisation models like MARKAL/TIMES and MESSAGE use (1), but they may be adapted to be used with the time slices approach (2). For example Kannan et al. [61] presented such a model for the Swiss electricity system. Another example for the application of (2) is the LIMES model [59, 140]. The application of real time series (3) can mainly be found in electricity system models [141, 142]. There are also hybrid models where long term energy system models are linked to short term operational power system models [53, 54, 60].

The weather dependency of RES potentials requires highly resolved data in space. However, such spatially resolved data is generally only available in annual values (e.g. in [143] where the annual RES potentials on a district level for Austria are presented). A newer approach is the renewable.nija database which provides time and space resolved PV and wind potentials [131, 144]. The spatial distribution of demand was mainly addressed for the heating sector by two studies which investigated the heat demand in the UK [73, 74]. It was found that different levels of spatial resolution or aggregation also require a simplification of the energy networks. Network reduction is currently an important field for modellers of large-scale transmission power grids [62, 75, 77, 145, 146]. This is also an important consideration when modelling MES at a distribution level.

The cellular approach [147] is a method that supports network reduction. The studied area is divided into a number of cells, based on local conditions like consumers, producers and energy infrastructure. All individual entities of the same type within a cell are aggregated and represented by one single cell. Because the internal load flows of a cell are neglected, network reduction methods are necessary so that inter-cellular load flows are correctly represented. Because of the averaging effect of aggregation, the cellular approach allows the utilisation of standardised or synthetic load profiles if no high resolution data is available.

Conclusions

In this paper, we presented an overview of the current research and challenges of modelling grid-based MES. General and specific aspects of modelling grid-based energy carrier systems have been provided.

In order to provide a robust and efficient future energy supply, MES models should incorporate the interactions between different energy carriers, and the representation of load flows in grids. They should also enable the cost efficient integration of high shares of RES by using available synergies the different energy grids provide. The aspects which necessitate a power-based perspective in future planning models have been discussed. These aspects include the representation of modelling details, temporal and spatial resolutions, and network representations. Presented are three open source modelling frameworks that have been tested and used by the authors.

The challenges discussed show that there are still wide gaps and several opportunities for future research topics. From a technical perspective, the amalgamation of planning and operational models [11] is a major challenge. This is because it demands finer temporal and spatial resolutions and requires the implementation of a lot more technical details into the model. Moreover, the complexity of a model increases when accounting for interdisciplinary aspects such as the interdependency of the food and water sector [29], or human behaviour in an energy system. The most common model families, like simulation and optimisation, might not be sufficient for solving the resulting (usually non-linear) mathematical problem. Model coupling or new modelling approaches like agent-based-modelling might be necessary to obtain robust and relevant results.

Endnotes

[1] The flexibilities offered by one energy carrier that can be used by another energy carrier, e.g. the enormous storage capacity of the natural gas grid is used with power-to-gas plants [24].

[2] For example, World Energy Model (WEM), National Energy Modelling System – Residential Sector Demand Module (NEMS-RSDM)

[3] For example, MARKAL/TIMES, MESSAGE

[4] For example, Prospective Outlook on Long-term Energy System (POLES), Price-Induced Market Equilibrium System (PRIMES)

[5] https://www.neplan.ch

[6] https://www.siemens.com/sincal

[7] https://www.digsilent.de/de/powerfactory.html

[8] Linepack is the quantity of gas contained in the pipe at a given time [98].

[9] www.github.com

[10] A commit is a contribution to a github project.

Additional file

Additional file 1: Additional file 1 includes the complete collection of open source energy modelling tools established from [25, 125, 126]. It includes: information regarding the host, the software license, the programming language, the mathematical model formulation, the availability of a documentation, the scope, the available energy sectors, possible time-resolutions and geo-resolutions, suitability to model multiple regions, and the possibility to model energy grids. (XLSX 20 kb)

Abbreviations

CHP: Combined heat and power; COP 21: 2015 United Nations Climate Change Conference; DP: Dynamic programming; EENS: Expected energy not served; LOEE: Loss of energy expectation; LOLE: Loss of load expectation LOLP: Loss of load probability; LP: Linear programming; MES: Multi-energy systems; MILP: Mixed-integer linear programming; NLMIP: Non-linear mixed-integer programming; RES: Renewable energy sources; VPP: Virtual power plant

Acknowledgements

Not applicable.

Funding

Not applicable.

Availability of data and materials
All the data supporting the conclusions is included in the text. The source codes of the open source modelling frameworks are available on github; links are cited within the text.

Authors' contributions
The main work was conducted by LK: MES literature review and current challenges on energy systems modelling. GS carried out the analysis of open source energy modelling frameworks. TK initialised the work and revised and approved the final manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 4 March 2018 Accepted: 17 October 2018
Published online: 13 November 2018

References
1. International Energy Agency (2017) Key world energy statistics: also available on smartphones and tablets. IEA Publications, Paris
2. Moriarty P, Honnery D (2012) What is the global potential for renewable energy? Renew Sust Energ Rev 16(1):244–252. https://doi.org/10.1016/j.rser.2011.07.15
3. Lewis NS, Nocera DG (2006) Powering the planet: Chemical challenges in solar energy utilization. Proc Natl Acad Sci U S A 103(43):15729–15735. https://doi.org/10.1073/pnas.060339510
4. CO2 Emissions From Fuel Combustion (2017) Overview (International Energy Agency, ed.). Organization for Economic Cooperation & Development and Rowman & Littlefield Publishers, Incorporated, Paris
5. United Nations Framework Convention of Climate Change (2015) United Nations Framework Convention on Climate Change: adoption of the Paris agreement (United Nations Framework Convention of Climate Change, ed.). United Nations, Paris. https://unfccc.int/sites/default/files/english_paris_agreement.pdf. Accessed 27 Oct 2018
6. Helm D (2002) Energy policy: security of supply, sustainability and competition. Energy Policy 30(3):173–184
7. Strachan N, Fais B, Daly H (2016) Reinventing the energy modelling–policy interface. Nat Energy 1(3):16012. https://doi.org/10.1038/nenergy.2016.1
8. Huntington H, Weyant JP, Sweeney JL (1982) Modeling for insights, not numbers: the experiences of the energy modeling forum. Omega 10(5):449–462. https://doi.org/10.1016/0305-0483(82)90002-0
9. Dantzig GB (1965) Linear programming and extensions. Second printing with corrections edn. Princeton University Press, Princeton
10. Zimmermann HJ (2005) Operations research: Methoden und Modelle ; Für Wirtschaftsingenieure, Betriebswirte, Informatiker. 1. aufl edn. Mathematik für Wirtschaftswissenschaftler. Vieweg, Wiesbaden
11. Pfenninger S, Hawkes A, Keirstead J (2014) Energy systems modeling for twenty-first century energy challenges. Renew Sust Energ Rev 33:74–86. https://doi.org/10.1016/j.rser.2014.02.00
12. Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I (2017) The importance of open data and software: Is energy research lagging behind? Energy Policy 101:211–215. https://doi.org/10.1016/j.enpol.2016.11.04
13. Cao KK, Cebulla F, Gómez Vilchez JJ, Mousavi B, Prehofer S (2016) Raising awareness in model-based energy scenario studies—a transparency checklist. Energy Sustain Soc 6(1):519. https://doi.org/10.1186/s13705-016-0090-z
14. Morrison R (2018) Energy system modeling: Public transparency, scientific reproducibility, and open development. Energy Strateg Rev 20:49–63. https://doi.org/10.1016/j.esr.2017.12.01
15. Collins S, Deane JP, Poncelet K, Panos E, Pietzcker RC, Delarue E, Ó Gallachóir BP (2017) Integrating short term variations of the power system into integrated energy system models: A methodological review. Renew Sust Energ Rev 76:839–856. https://doi.org/10.1016/j.rser.2017.03.09
16. IEA-ETSAP (2008) MARKAL: MARket ALlocation. IEA-ETSAP. http://iea-etsap.org/index.php/etsap-tools/model-generators/markal. Accessed 04 Dec 2017
17. Agnew M, Schrattenholzer L, Voss A (2017) A model for energy supply systems alternatives and their general environmental impact. IIASA, Laxenburg, Austria. http://pure.iiasa.ac.at/1177/. Accessed 07 Dec 2017
18. Messner S (1984) User's guide for the matrix generator of message II. Parts I and II: Model Description and Implementation Guide, and Appendices. IIASA, Laxenburg, Austria. http://pure.iiasa.ac.at/2447/. Accessed 07 Dec 2017
19. Mancarella P, Andersson G, Pecas-Lopes JA, Bell KRW (2016) Modelling of integrated multi-energy systems: drivers, requirements, and opportunities. In: 2016 Power Systems Computation Conference (PSCC). IEEE. pp 1–22. https://doi.org/10.1109/PSCC.2016.754103
20. Brauner G (2016) Energiesysteme: Regenerativ und Dezentral. Springer Fachmedien Wiesbaden, Wiesbaden. https://doi.org/10.1007/978-3-658-12755-8
21. Ruiz-Romero S, Colmenar-Santos A, Mur-Pérez F, López-Rey Á (2014) Integration of distributed generation in the power distribution network: the need for smart grid control systems, communication and equipment for a smart city — Use cases. Renew Sust Energ Rev 38:223–234. https://doi.org/10.1016/j.rser.2014.05.08
22. Heimberger M, Kaufmann T, Maier C, Nemec-Begluk S, Winter A, Gawlik W (2017) Energieträgerübergreifende Planung und Analyse von Energiesystemen. Elektrotechnik Informationstechnik 134(3):229–237. https://doi.org/10.1007/s00502-017-0504-
23. Heinrichs HU (2013) Analyse der Langfristigen Auswirkungen Von Elektromobilität Auf Das Deutsche Energiesystem Im Europäischen Energieverbund. In: Produktion und Energie / Karlsruher Institut für Technologie, Institut für Industriebetriebslehre und industrielle Produktion u. Deutsch-Französisches Institut für Umweltforschung, vol. 5, Print on demand edn. KIT Scientific Publishing, Karlsruhe
24. O'Malley M, Kroposki B, Hannegan B, Madsen H, Andersson M, D'haeseleer W, McGranaghan MF, Dent C, Strbac G, Baskaran S, Rinker M (2016) Energy Systems Integration. Defining and Describing the Value Proposition. https://doi.org/10.2172/125767
25. Energypedia (2017) openmod intiative. https://wiki.openmod-initiative.org/wiki/Open_Models. Accessed 17 Nov 2017
26. Pfenninger S, Hirth L, Schlecht I, Schmid E, Wiese F, Brown T, Davis C, Gidden M, Heinrichs H, Heuberger C, Hilpert S, Krien U, Matke C, Nebel A, Morrison R, Müller B, Pleßmann G, Reeg M, Richstein JC, Shivakumar A, Staffell I, Tröndle T, Wingenbach C (2018) Opening the black box of energy modelling: Strategies and lessons learned. Eng Strateg Rev 19:63–71. https://doi.org/10.1016/j.esr.2017.12.00
27. (2012) Global Energy Assessment (GEA): Toward a Sustainable Future. 1. publ edn(Johansson TB, ed.). Cambridge Univ. Press, Cambridge u.a.
28. Mancarella P (2014) MES (multi-energy systems): An overview of concepts and evaluation models. Energy 65:1–17. https://doi.org/10.1016/j.energy.2013.10.04
29. Wiese F, Hilpert S, Kaldemeyer C, Pleßmann G (2018) A qualitative evaluation approach for energy system modelling frameworks. Energy Sustain Soc 8(1):211. https://doi.org/10.1186/s13705-018-0154-3
30. Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Yousefi H (2017) Energy hub: from a model to a concept – a review. Renew Sust Energ Rev 80:1512–1527. https://doi.org/10.1016/j.rser.2017.07.03
31. Keirstead J, Jennings M, Sivakumar A (2012) A review of urban energy system models: approaches, challenges and opportunities. Renew Sust Energ Rev 16(6):3847–3866. https://doi.org/10.1016/j.rser.2012.02.04
32. van Beuzekom I, Gibescu M, Slootweg JG (2015) A review of multi-energy system planning and optimization tools for sustainable urban development. In: 2015 IEEE Eindhoven PowerTech. pp 1–7. https://doi.org/10.1109/PTC.2015.723236. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7232360
33. Hall LMH, Buckley AR (2016) A review of energy systems models in the UK: prevalent usage and categorisation. Appl Energy 169:607–628. https://doi.org/10.1016/j.apenergy.2016.02.04

34. Syranidis K, Robinius M, Stolten D (2018) Control techniques and the modeling of electrical power flow across transmission networks. Renew Sust Energ Rev 82:3452–3467. https://doi.org/10.1016/j.rser.2017.10.11
35. Box GEP, Draper NR (1987) Empirical model-building and response surfaces. Wiley Ser Probab Math Stat. Wiley, Oxford
36. Herbst A, Toro F, Reitze F, Jochem E (2012) Introduction to energy systems modelling. Swiss J Econ Stat 148(2):111–135. https://doi.org/10.1007/BF0339936
37. Connolly D, Lund H, Mathiesen BV, Leahy M (2010) A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 87(4):1059–1082. https://doi.org/10.1016/j.apenergy.2009.09.02
38. Thiem S (2017) Multi-modal on-site energy systems: development and application of a superstructure-based optimization method for energy system design under consideration of part-load efficiencies. PhD, Technische Universität München, München
39. Palensky P, Widl E, Stifter M, Elsheikh A (2013) Modeling intelligent energy systems: co-simulation platform for validating flexible-demand EV charging management. IEEE Trans Smart Grid 4(4):1939–1947. https://doi.org/10.1109/TSG.2013.225805
40. Palensky P, Widl E, Elsheikh A (2014) Simulating cyber-physical energy systems: challenges, tools and methods. IEEE Trans Syst Man Cybern Syst 44(3):318–326. https://doi.org/10.1109/TSMCC.2013.226573
41. van Beeck NMJP (1999) Classification of energy models. FEW Research Memorandum. Operations research, Tilburg
42. Ommen T, Markussen WB, Elmegaard B (2014) Comparison of linear, mixed integer and non-linear programming methods in energy system dispatch modelling. Energy 74:109–118. https://doi.org/10.1016/j.energy.2014.04.02
43. (2016) The physics of stocks and flows of energy systems. SpringerBriefs in Complexity(Qudrat-Ullah H, ed.). Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-24829-
44. Wagner PH, Wittmann M (2014) Influence of different operation strategies on transient solar thermal power plant simulation models with molten salt as heat transfer fluid. Energy Procedia 49:1652–1663. https://doi.org/10.1016/j.egypro.2014.03.17
45. Steen D, Stadler M, Cardoso G, Groissböck M, DeForest N, Marnay C (2015) Modeling of thermal storage systems in MILP distributed energy resource models. Appl Energy 137:782–792. https://doi.org/10.1016/j.apenergy.2014.07.03
46. Gönen T, Foote BL (1982) Mathematical dynamic optimization model for electrical distribution system planning. Int J Electr Power Energy Syst 4(2):129–136. https://doi.org/10.1016/0142-0615(82)90039-4
47. Tashiro T, Tamura K, Yasuda K (2011) Modeling and optimal operation of distributed energy systems via dynamic programming. In: 2011 IEEE International Conference on Systems, Man, and Cybernetics. IEEE. pp 808–813. https://doi.org/10.1109/ICSMC.2011.608375
48. Bell KRW, Tleis AND (2010) Test system requirements for modelling future power systems. In: IEEE PES General Meeting. IEEE. pp 1–8. https://doi.org/10.1109/PES.2010.558980
49. Aien M, Hajebrahimi A, Fotuhi-Firuzabad M (2016) A comprehensive review on uncertainty modeling techniques in power system studies. Renew Sust Energ Rev 57:1077–1089. https://doi.org/10.1016/j.rser.2015.12.07
50. Aien M, Rashidinejad M, Fotuhi-Firuzabad M (2014) On possibilistic and probabilistic uncertainty assessment of power flow problem: A review and a new approach. Renew Sust Energ Rev 37:883–895. https://doi.org/10.1016/j.rser.2014.05.06
51. Zadeh LA (1999) Fuzzy sets as a basis for a theory of possibility. Fuzzy Sets Syst 100:9–34. https://doi.org/10.1016/S0165-0114(99)80004-9
52. Cai YP, Huang GH, Yang ZF, Tan Q (2009) Identification of optimal strategies for energy management systems planning under multiple uncertainties. Appl Energy 86(4):480–495. https://doi.org/10.1016/j.apenergy.2008.09.02
53. Poncelet K, Delarue E, Six D, Duerinck J, D'haeseleer W (2016) Impact of the level of temporal and operational detail in energy-system planning models. Appl Energy 162:631–643. https://doi.org/10.1016/j.apenergy.2015.10.10
54. Deane JP, Chiodi A, Gargiulo M, Ó Gallachóir BP (2012) Soft-linking of a power systems model to an energy systems model. Energy 42(1):303–312. https://doi.org/10.1016/j.energy.2012.03.05
55. Welsch M, Mentis D, Howells M (2014) Long-term energy systems planning. In: Jones LE (ed). Renewable Energy Integration. Elsevier. pp 215–225. https://doi.org/10.1016/B978-0-12-407910-6.00017-X
56. van Stiphout A, de Vos K, Deconinck G (2017) The impact of operating reserves on investment planning of renewable power systems. IEEE Trans Power Syst 32(1):378–388. https://doi.org/10.1109/TPWRS.2016.256505
57. Palmintier B (2014) Flexibility in generation planning: identifying key operating constraints. In: 2014 Power Systems Computation Conference. IEEE. pp 1–7. https://doi.org/10.1109/PSCC.2014.703832
58. Haydt G, Leal V, Pina A, Silva CA (2011) The relevance of the energy resource dynamics in the mid/long-term energy planning models. Renew Energy 36(11):3068–3074. https://doi.org/10.1016/j.renene.2011.03.02
59. Ludig S, Haller M, Schmid E, Bauer N (2011) Fluctuating renewables in a long-term climate change mitigation strategy. Energy 36(11):6674–6685. https://doi.org/10.1016/j.energy.2011.08.02
60. Pina A, Silva CA, Ferrão P (2013) High-resolution modeling framework for planning electricity systems with high penetration of renewables. Appl Energy 112:215–223. https://doi.org/10.1016/j.apenergy.2013.05.07
61. Kannan R, Turton H (2013) A long-term electricity dispatch model with the TIMES framework. Environ Model Assess 18(3):325–343. https://doi.org/10.1007/s10666-012-9346-
62. Koltsaklis NE, Dagoumas AS, Kopanos GM, Pistikopoulos EN, Georgiadis MC (2014) A spatial multi-period long-term energy planning model: a case study of the Greek power system. Appl Energy 115:456–482. https://doi.org/10.1016/j.apenergy.2013.10.04
63. Biberacher M, Gadocha S, Vliet O (2013) EnviroInfo 2013 - Environmental Informatics and Renewable Energies. In: Page B, Fleischer AG, Göbel J, Wohlgemuth V (eds). Shaker, Aachen
64. Dyckhoff H, Spengler TS (2007) Produktionswirtschaft: Eine Einführung Für Wirtschaftsingenieure ; Mit 10 Tabellen. 2, verb. aufl. edn. Springer-Lehrbuch. Springer, Berlin and Heidelberg. https://doi.org/10.1007/978-3-540-72218-. http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10187412
65. Reynolds J, Ahmad MW, Rezgui Y (2018) Holistic modelling techniques for the operational optimisation of multi-vector energy systems. Energy Build 169:397–416. https://doi.org/10.1016/j.enbuild.2018.03.06
66. Kerdoncuff P (2008) Modellierung und Bewertung Von Prozessketten zur Herstellung Von Biokraftstoffen der Zweiten Generation: Zugl.: Karlsruhe, Univ., Diss. Univ.-Verl. Karlsruhe, Karlsruhe
67. Li X, Wen J (2014) Review of building energy modeling for control and operation. Renew Sust Energ Rev 37:517–537. https://doi.org/10.1016/j.rser.2014.05.05
68. Good N, Zhang L, Navarro-Espinosa A, Mancarella P (2015) High resolution modelling of multi-energy domestic demand profiles. Appl Energy 137:193–210. https://doi.org/10.1016/j.apenergy.2014.10.02
69. Corrado V, Fabrizio E, Filippi M (2007) Modelling and optimization of multi-energy source building systems in the design concept phase. In: Proceedings of Clima 2007
70. van Beuzekom I, Gibescu M, Pinson P, Slootweg JG (2017) Optimal planning of integrated multi-energy systems. In: 2017 IEEE Manchester PowerTech. pp 1–6. https://doi.org/10.1109/PTC.2017.798088. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7980886
71. Lund H, Mathiesen BV (2009) Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050. Energy 34(5):524–531. https://doi.org/10.1016/j.energy.2008.04.00
72. Pillai JR, Heussen K, Østergaard PA (2011) Comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios. Energy 36(5):3233–3243. https://doi.org/10.1016/j.energy.2011.03.01
73. Li F (2013) Spatially explicit techno-economic optimisation modelling of UK heating futures
74. Munuera L (2014) Technology—rich economic modelling and analysis of residential heating systems for low carbon energy policy support
75. Di Shi, Tylavsky DJ (2015) A Novel Bus-Aggregation-Based Structure-Preserving Power System Equivalent. IEEE Trans Power Syst 30(4):1977–1986. https://doi.org/10.1109/TPWRS.2014.235944
76. Horsch J, Brown T (2017) The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios. In: 2017 14th International Conference on the European Energy Market (EEM). IEEE. pp 1–7. https://doi.org/10.1109/EEM.2017.798202

77. Corcoran BA, Jenkins N, Jacobson MZ (2012) Effects of aggregating electric load in the United States. Energy Pol 46:399–416. https://doi.org/10.1016/j.enpol.2012.03.07
78. Hawkes AD, Leach MA (2005) Impacts of temporal precision in optimisation modelling of micro-Combined Heat and Power. Energy 30(10):1759–1779. https://doi.org/10.1016/j.energy.2004.11.01
79. Martens A (1998) The energetic feasibility of CHP compared to the separate production of heat and power. Appl Therm Eng 18(11):935–946. https://doi.org/10.1016/S1359-4311(98)00026-X
80. Wall G (1977) Exergy: A useful concept within resource accounting
81. Billinton R, Allan RN (1996) Reliability evaluation of power systems. 2nd ed. Plenum Press, New York
82. Geidl M, Koeppel G, Perrod PF, Klockl B, Andersson G, Frohlich K (2007) Energy hubs for the future. IEEE Power Energy Mag 5(1):24–30. https://doi.org/10.1109/MPAE.2007.26485
83. Schavemaker P, van der Sluis L (2009) Electrical power system essentials. Reprint. with corr edn. Wiley, Chichester
84. Medjroubi W, Müller UP, Scharf M, Matke C, Kleinhans D (2017) Open data in power grid modelling: new approaches towards transparent grid models. Energy Rep 3:14–21. https://doi.org/10.1016/j.egyr.2016.12.00
85. Kile H, Uhlen K, Warland L, Kjolle G (2014) A comparison of AC and DC power flow models for contingency and reliability analysis. In: 2014 Power Systems Computation Conference. IEEE. pp 1–7. https://doi.org/10.1109/PSCC.2014.703845
86. Gunkel D, Most D (2014) The German transmission grid expansion in long-term perspective — What is the impact of renewable integration? In: 11th International Conference on the European Energy Market (EEM14). IEEE. pp 1–6. https://doi.org/10.1109/EEM.2014.686121
87. Mobius T, Gunkel D (2014) The optimal placing of energy storages in Germany in 2020—an implementation of a DC-load flow model. In: 11th International Conference on the European Energy Market (EEM14). IEEE. pp 1–5. https://doi.org/10.1109/EEM.2014.686124
88. Sahin C (2018) Consideration of network constraints in the Turkish day ahead electricity market. Int J Electr Power Energy Syst 102:245–253. https://doi.org/10.1016/j.ijepes.2018.04.02
89. Eldridge B, O'Neill R, Castillo A (2018) An improved method for the DCOPF with losses. IEEE Trans Power Syst 33(4):3779–3788. https://doi.org/10.1109/TPWRS.2017.277608
90. Murari K, Padhy NP (2018) A network-topology based approach for the load flow solution of AC-DC distribution system with distributed generations. IEEE Trans Ind Inf:1. https://doi.org/10.1109/TII.2018.285271
91. Fathtabar H, Barforoushi T, Shahabi M (2018) Dynamic long-term expansion planning of generation resources and electric transmission network in multi-carrier energy systems. Int J Electr Power Energy Syst 102:97–109. https://doi.org/10.1016/j.ijepes.2018.04.01
92. Frank S, Steponavice I, Rebennack S (2012) Optimal power flow: a bibliographic survey I. Energy Syst 3(3):221–258. https://doi.org/10.1007/s12667-012-0056-y
93. Geidl M, Andersson G (2007) Optimal power flow of multiple energy carriers. IEEE Trans Power Syst 22(1):145–155. https://doi.org/10.1109/TPWRS.2006.88898
94. Xu X, Li K, Liu Y, Jia H (2016) Integrated optimal power flow for distribution networks in local and urban scales. In: 2016 UKACC 11th International Conference on Control (CONTROL). IEEE. pp 1–6. https://doi.org/10.1109/CONTROL.2016.773752
95. Almassalkhi M, Hiskens I (2011) Optimization framework for the Analysis of large-scale networks. In: Proceedings of 17th Power Systems Computation Conference. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6161484
96. Liu X, Yuan CL, Liu XY, Luo F-h, Feng Q, Xu J, Chen GH, Zhou CR (2016) Microstructures, electrical behavior and energy-storage properties of Ba0.06Na0.47Bi0.47TiO3-Ln1/3NbO3 (Ln = La, Nd, Sm) ceramics. Mater Chem Phys 181:444–451. https://doi.org/10.1016/j.matchemphys.2016.06.08
97. Liu C, Shahidehpour M, Wang J (2011) Coordinated scheduling of electricity and natural gas infrastructures with a transient model for natural gas flow. Chaos (Woodbury, N.Y.) 21(2):025102. https://doi.org/10.1063/1.360076
98. Clegg S, Mancarella P (2016) Integrated electrical and gas network flexibility assessment in low-carbon multi-energy systems. In: 2016 IEEE Power and Energy Society General Meeting (PESGM). IEEE. p 1. https://doi.org/10.1109/PESGM.2016.774150
99. Li Z, Wu W, Wang J, Zhang B, Zheng T (2016) Transmission-constrained unit commitment considering combined electricity and district heating networks. IEEE Trans Sust Energy 7(2):480–492. https://doi.org/10.1109/TSTE.2015.250057
100. Geidl M (2007) Integrated modeling and optimization of multi-carrier energy systems. Dissertation. ETH Zürich, Zürich
101. Morvaj B, Evins R, Carmeliet J (2017) Comparison of individual and microgrid approaches for a distributed multi energy system with different renewable shares in the grid electricity supply. Energy Procedia 122:349–354. https://doi.org/10.1016/j.egypro.2017.07.33
102. Asmus P (2010) Microgrids, virtual power plants and our distributed energy future. Electr J 23(10):72–82. https://doi.org/10.1016/j.tej.2010.11.00
103. Heussen K, Koch S, Ulbig A, Andersson G (2010) Energy storage in power system operation: the power nodes modeling framework. In: 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe). pp 1–8. https://doi.org/10.1109/ISGTEUROPE.2010.563886. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5638865
104. Geidl M, Andersson G (2005) Operational and topological optimization of multi-carrier energy systems. In: 2005 International Conference on Future Power Systems. pp 6–6. https://doi.org/10.1109/FPS.2005.20419. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1600472
105. Andersson G, Fröhlich K, Krause T (2011) Vision of future energy networks (VoFEN): Schlussbericht: Phase 2, Zürich
106. Geidl M, Andersson G (2005) Optimal power dispatch and conversion in systems with multiple energy carriers. In: Proceedings of the 15th Power System Computation Conference (PSSC)
107. Koeppel G (2007) Reliability considerations of future energy systems: multi-carrier systems and the effect of energy storage. Dissertation
108. Krause T, Kienzle F, Art S, Andersson G (2010) Maximizing exergy efficiency in multi-carrier energy systems. In: Energy Society General Meeting. pp 1–8. https://doi.org/10.1109/PES.2010.558999
109. Lasseter RH (2011) Smart distribution: coupled microgrids. Proc IEEE 99(6):1074–1082. https://doi.org/10.1109/JPROC.2011.211463
110. Piacentino A, Barbaro C, Cardona F, Gallea R, Cardona E (2013) A comprehensive tool for efficient design and operation of polygeneration-based energy micro-grids serving a cluster of buildings. Part I: Description of the method. Appl Energy 111:1204–1221. https://doi.org/10.1016/j.apenergy.2012.11.07
111. Piacentino A, Barbaro C (2013) A comprehensive tool for efficient design and operation of polygeneration-based energy micro-grids serving a cluster of buildings. Part II: Analysis of the applicative potential. Appl Energy 111:1222–1238. https://doi.org/10.1016/j.apenergy.2012.11.07
112. Bracco S, Delfino F, Pampararo F, Robba M, Rossi M (2014) A mathematical model for the optimal operation of the University of Genoa Smart Polygeneration Microgrid: evaluation of technical, economic and environmental performance indicators. Energy 64:912–922. https://doi.org/10.1016/j.energy.2013.10.03
113. Corera J (2009) FENIX: Flexible electricity networks to integrate the expected energy evolution: results. http://www.fenix-project.org/. Accessed 22 Nov 2017
114. Ropenus S, Skytte K (2005) Regulatory review and barriers for the electricity supply system for distributed generation in EU-15. In: 2005 International Conference on Future Power Systems. pp 6–6. https://doi.org/10.1109/FPS.2005.20426. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1600534
115. eex group (2018) EEX Exchange Rules, Leipzig. https://www.eex.com/blob/80166/898f6187342da3502e48b4516b96a42c/eex-exchange-rules-en-data.pdf. Accessed 24 May 2018
116. Austrian Power Grid (2017) Conditions for participation in tenders for control energy. https://www.apg.at/en/market/balancing/conditions-for-participation. Accessed 22 Nov 2017
117. German transmission system operators (2017) regelleistung.net: Internetplattform zur Vergabe von Regelleistung. www.regelleistung.net. Accessed 22 Nov 2017
118. Wille-Haussmann B, Erge T, Wittwer C (2010) Decentralised optimisation of cogeneration in virtual power plants. Solar Energy 84(4):604–611. https://doi.org/10.1016/j.solener.2009.10.00
119. Wang D, Parkinson S, Miao W, Jia H, Crawford C, Djilali N (2013) Hierarchical market integration of responsive loads as spinning reserve. Appl Energy 104:229–238. https://doi.org/10.1016/j.apenergy.2012.10.05

120. Kusch W, Schmidla T, Stadler I (2012) Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables. Energy 48(1):153–159. https://doi.org/10.1016/j.energy.2012.06.05
121. Lind M (2011) An introduction to multilevel flow modeling. Int J Nucl Saf Simul 2(1):22–32
122. Heussen K, Koch S, Ulbig A, Andersson G (2012) Unified system-level modeling of intermittent renewable energy sources and energy storage for power system operation. IEEE Syst J 6(1):140–151. https://doi.org/10.1109/JSYST.2011.216302
123. Heussen K (2011) Control architecture modeling for future power systems
124. Bakken BH, Holen AT (2004) Energy service systems: integrated planning case studies. In: IEEE Power Engineering Society General Meeting, 2004. pp 2068–2073. https://doi.org/10.1109/PES.2004.137324. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1373245
125. EnergyPLAN (2017) Other tools: links to energy system analysis models. http://www.energyplan.eu/othertools/. Accessed 24 Nov 2017
126. Wikipedia (2017) Open energy system models. https://en.wikipedia.org/wiki/Open_energy_system_models. Accessed 23 Nov 2017
127. Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, Tveten ÅG, Bolkesjø TF, Münster M, Ravn H (2018) Balmorel open source energy system model. Energy Strat Rev 20:26–34. https://doi.org/10.1016/j.esr.2018.01.00
128. Atabay D (2017) An open-source model for optimal design and operation of industrial energy systems. Energy 121:803–821. https://doi.org/10.1016/j.energy.2017.01.03
129. Brown T, Hörsch J, Schlachtberger D (2018) PyPSA: Python for power system analysis. J Open Res Softw 6(3):12. https://doi.org/10.5334/jors.18
130. Andresen L, Dubucq P, Peniche Garcia R, Ackermann G, Kather A, Schmitz G (2015) Status of the transient library: transient simulation of coupled energy networks with high share of renewable energy. In: Linköping Electronic Conference Proceedings. Linköping University Electronic Press. pp 695–705. https://doi.org/10.3384/ecp1511869
131. Pfenninger S (2017) Dealing with multiple decades of hourly wind and PV time series in energy models: a comparison of methods to reduce time resolution and the planning implications of inter-annual variability. Appl Energy 197:1–13. https://doi.org/10.1016/j.apenergy.2017.03.05
132. oemof Developer Group (2017) Open Energy Modelling Framework (Oemof) - A Modular Open Source Framework To Model Energy Supply Systems. Version V0.1.4. Zenodo. https://doi.org/10.5281/zenodo.43867
133. Dorfner J, Dorfner M, Schönleber K, Zipperle T, Herzog S, Siala K, Akca O (2017) Tum-Ens/Urbs: V0.7.2. Zenodo. https://doi.org/10.5281/zenodo.59420
134. Hilpert S, Günther S, Kaldemeyer C, Krien U, Plessmann G, Wiese F, Wingenbach C (2017) Addressing energy system modelling challenges: the contribution of the open energy modelling framework (oemof). https://doi.org/10.20944/preprints201702.0055.v
135. Fisk DJ, Kerhervé J (2006) Complexity as a cause of unsustainability. Ecol Complex 3(4):336–343. https://doi.org/10.1016/j.ecocom.2007.02.00
136. Ulanowicz RE, Goerner SJ, Lietaer B, Gomez R (2009) Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol Complex 6(1):27–36. https://doi.org/10.1016/j.ecocom.2008.10.00
137. Hughes N, Strachan N (2010) Methodological review of UK and international low carbon scenarios. Energy Pol 38(10):6056–6065. https://doi.org/10.1016/j.enpol.2010.05.06
138. Strbac G (2008) Demand side management: Benefits and challenges. Energy Pol 36(12):4419–4426. https://doi.org/10.1016/j.enpol.2008.09.03
139. Kiureghian AD, Ditlevsen O (2009) Aleatory or epistemic? Does it matter? Struct Saf 31(2):105–112. https://doi.org/10.1016/j.strusafe.2008.06.02
140. Haller M, Ludig S, Bauer N (2012) Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation. Energy Pol 47:282–290. https://doi.org/10.1016/j.enpol.2012.04.06
141. Fripp M (2012) Switch: A planning tool for power systems with large shares of intermittent renewable energy. Environ Sci Technol 46(11):6371–6378. https://doi.org/10.1021/es204645
142. Pfluger B, Wietschel M (2012) Impact of renewable energies on conventional power generation technologies and infrastructures from a long-term least-cost perspective. In: 2012 9th International Conference on the European Energy Market. IEEE. pp 1–10. https://doi.org/10.1109/EEM.2012.625476
143. Stanzer G, Novak S, Dumke H, Plha S, Schaffer H, Breinesberger J, Kirtz M, Biermayer P, Spanring C REGIO Energy: Regionale Szenarien erneuerbarer Energiepotenziale in den Jahren 2012/2020, Wien and St. Pölten. http://regioenergy.oir.at/sites/regioenergy.oir.at/files/uploads/pdf/REGIO-Energy_Endbericht_201013_korr_Strom_Waerme.pdf. Accessed 12 Jan 2018
144. Staffell I, Pfenninger S (2016) Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114:1224–1239. https://doi.org/10.1016/j.energy.2016.08.06
145. Shawhan D, Taber J, Zimmerman R, Yan J, Marquet C, Schulze W, Schuler R, Thomas R, Tylavsky D, Shi D, Li N, Jewell W, Hardy T, Hu Z (2015) A detailed power system planning model: estimating the long-run impact of carbon-reducing policies. In: 2015 48th Hawaii International Conference on System Sciences. IEEE. pp 2497–2506. https://doi.org/10.1109/HICSS.2015.30
146. Schlachtberger DP, Brown T, Schramm S, Greiner M (2017) The benefits of cooperation in a highly renewable European electricity network. Energy 134:469–481. https://doi.org/10.1016/j.energy.2017.06.00
147. Böckl B, Kriechbaum L, Kienberger T (2016) Analysemethode für kommunale Energiesysteme unter Anwendung des zellularen Ansatzes. In: Institut für Elektrizitätswirtschaft und Energieinnovation (ed.) 14. Symposium Energieinnovation. TU Graz, Graz

11 PAPER 2

Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation.

energies

MDPI

Article

Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation

Lukas Kriechbaum * and **Thomas Kienberger**

Chair of Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef Straße 18, A-8700 Leoben, Austria; thomas.kienberger@unileoben.ac.at

* Correspondence: lukas.kriechbaum@unileoben.ac.at; Tel.: +43-3842-402-5408

Received: 25 November 2019; Accepted: 26 December 2019; Published: 1 January 2020

check for updates

Abstract: In developed countries like Austria the renewable energy potential might outpace the demand. This requires primary energy efficiency measures as well as an energy system design that enables the integration of variable renewable energy sources. Municipal energy systems, which supply customers with heat and electricity, will play an important role in this task. The cumulative exergy consumption methodology considers resource consumption from the raw material to the final product. It includes the exergetic expenses for imported energy as well as for building the energy infrastructure. In this paper, we determine the exergy optimal energy system design of an exemplary municipal energy system by using cumulative exergy consumption minimisation. The results of a case study show that well a linked electricity and heat system using heat pumps, combined heat power plants and battery and thermal storages is necessary. This enables an efficient supply and also provides the necessary flexibilities for integrating variable renewable energy sources.

Keywords: energy systems optimisation; exergy analysis; cumulative-exergy consumption minimisation; multi-energy systems; energy-system design; municipal energy systems

1. Introduction

Recent studies for Austria showed that the available potential for renewable energy sources (RES) is smaller than the current demand [1,2]. To reach the goal of a fully climate neutral society, imports of RES from other countries or local efficiency measures are necessary. In this context, exergy is a useful concept for identifying efficiency potentials. Although energy is subject to the law of conservation and can never be created or destroyed, exergy is the maximum useful work that can be extracted from a form of energy. It is consumed when brought to equilibrium with its surroundings, therefore it is a potential which describes the ability to cause change. It is the motive force that determines the flow of energy and it constantly deteriorates on its way through the energy system [3]. In the literature, there exist a variety of tools and methods [4,5] to identify and reduce exergy destruction and exergy losses. Their main aim is to increase resource efficiency.

The various forms of energy have different exergy contents, e.g., electricity is pure exergy, whereas low temperature heat has a very low exergy content. Most of today's used (fossil) energy carriers have a high exergy content. Data for 2016 shows that 50.7% of the final energy consumption in Austria is used for heat applications [6]. 66.1% of the heat is used for low temperature applications like domestic heating, hot water or air conditioning. The rest is used for steam or in furnaces in high temperature industrial applications. In a number of energy strategies of highly developed countries, the focus is on decarbonising the electric power generation [7], even though in the OECD member countries only 22.2% of the final energy consumption is electricity [8].

A comprehensive decarbonisation of the energy system requires efficiency measures and a replacement of fossil fuels by renewable electricity [9]. In multi-energy systems (MES) several sectors (e.g., electricity, heat and transport) and energy carriers (e.g., electricity, natural gas, biomass) are considered in an integrated approach [10]. The coupling of energy sectors and their infrastructures using suitable technologies (e.g., heat pumps, CHPs, etc.) enables the utilisation of synergies, and provides the necessary flexibility for integrating variable RES. MES can also relieve the strain on the energy transmission and distribution infrastructure [11,12].

Today's typical way of energy system optimisation often focus solely on the electricity system, mainly aiming at an optimum dispatch of power plants and storages. The well-developed electricity grid makes electricity an easy to transport good and establishes operational competition between the individual electricity producers. The present approach delivers optimum operational strategies for the whole system, but does not investigate its optimum design. For heat the situation is different, as heat supply is a local issue and individual buildings or small heat grids are usually supplied by one or few plants. The main decision regarding energy and exergy consumption of heat supply is made during the system design process, and the technology selection. Therefore the main two research questions which occur when designing an exergy efficient MES, where heat and electricity sectors are linked:

- What is the optimum system design? How can it provide the necessary flexibility options for the integration variable RES?
- How can this system be efficiently operated to always meet the demand?

This calls for a model which combines planning and operational aspects [13]. The cumulative exergy demand (CExC) methodology [14] includes both the above outlined points. Next to the exergy consumed during operation it also considers the exergy consumed to create the energy system's infrastructure.

In this paper, we present the application of the CExC-minimisation on municipal energy systems. First we present the current research and the relevant literature on exergy analysis and energy system optimisation in Section 2. This is followed by an introduction into the concept of exergy, the CExC methodology and the optimisation approach in Section 3. Section 4 presents the results from applying the methodology on a municipal energy system. We close this paper with a comprehensive discussion of the results in Section 5.

2. State of Research

The term exergy was first mentioned by Rant in 1953 when he described the "technical working capacity" [15]. Today, the concept of exergy is used in different kind of fields in environmental science and technology. In this section, the basics of exergy are first presented and then a literature overview of the current tools and methods of exergy analysis is given.

2.1. Fundamentals: Exergy, Exergy Destruction and Exergy Losses

The first law of thermodynamics describes the energy conservation. The second law indicates the irreversibility of natural processes. This means that in any real process, exergy is consumed and entropy is created. The second law also provides information regarding the convertibility of energy forms and the direction in which a process proceeds. For example, electricity or mechanical work theoretically can be fully converted into any other form of energy, whereas for instance for heat the convertibility depends on the temperature difference. In general, energy E consists of a useful part exergy B and the useless part anergy A.

$$E = B + A \quad (1)$$

Exergy is the useful work that can be theoretically extracted from a form of energy when it is brought to equilibrium with its ambient conditions. Anergy in contrary cannot conduct any work. A well-known example for anergy is heat at ambient temperature.

Four different forms contribute to the total exergy of a system: potential exergy B_{pot} (system height relative to the environment), kinetic exergy B_{kin} (system velocity relative to the environment), chemical exergy B_{ch} (deviation of the chemical composition to the environment) and physical exergy B_{ph} (deviation of pressure p and temperature ϑ from the environment p_0, ϑ_0) [5]. Potential and kinetic energy are pure exergy; the chemical exergy can be approximated by using the lower heating value [16]. The physical exergy, B_{ph}, of a mass, m, can be calculated by the enthalpy, h, and entropy, s, of a system with its p and ϑ compared to the ambient conditions (T_0, s_0).

$$B_{ph} = [(h - h_0) - (\vartheta_0 s - \vartheta_0 s_0)] \cdot m \tag{2}$$

Thermodynamic inefficiencies in an energy system are either caused by exergy destruction B_D or exergy losses B_L [17]. A well known example for exergy destruction is the production of hot water by burning natural gas. Irreversible thermodynamic transformations cause exergy destruction B_D by entropy generation s_{gen}. For a system with the mass m these irreversibilities can be described by the Guoy–Stodola theorem (Equation (3)). As exergy is always dependent on a reference state; it is usually described by the reference pressure p_0 and reference temperature ϑ_0. Commonly this reference is the "standard atmosphere".

$$B_D = \vartheta_0 s_{gen} \cdot m \tag{3}$$

Exergy losses B_L are caused by exergy transfers over the system boundaries. That might be work, heat or physical streams that cannot be further utilised. Examples are heat losses in a district heat network or flue gas exhaust streams from boilers.

2.2. Exergy Analysis: Tools and Methodologies

So far, for exergy analysis several tools and methodologies have been developed [4,5]. Examples are the the cumulative exergy consumption [14], the exergetic cost theory [18,19], thermoeconomics [20] or the extended exergy analysis [21]. They all share the same major goal to help to improve the system design, even though they have different system boundaries. As exergy is the potential to conduct work, it is especially suited as a common base in MES where different energy forms with different exergy contents are compared [16].

Cumulative exergy consumption (CExC) and the exergetic cost methodology extend exergy analysis of a single process beyond its boundaries to include all processes from natural resources to the final product. They both use a "fuel–product concept", where for any system a fuel exergy and a product exergy can be defined. Their exergetic definitions depend on the requirements of the task [18]. CExC analysis was introduced by Szargut in 1957 [22] and includes all exergetic expenses from raw materials to the final product [23]. The exergetic cost theory was introduced by Valero et al. [18] and is defined as "the sum of exergy contained in all resources entering the supply chain of the selected product or process" [5]. In this case, the term "cost" is the exergetic expenditure and has not monetary relation. Even though both methods use a different formalisation, their results are equivalent [5].

Both methodologies are applied to different fields. Szargut et al. [14] proposed the the CExC method to improve the "cumulative degree of perfection of chemical processes". Applications in energy conversion deal with an oxy-fuel combustion plant [24], or an organic Rankine cycle for waste heat power generation [25]. Valero et al. [26] applied the exergetic cost theory to the CGAM problem [27] and represented the productive structure explicitly, which allows optimisation at a local level. Lozano and Valero [28] performed an exergetic cost analysis on a steam boiler in a thermal generating station. In this study, the authors analysed variations in the exergetic costs of the total product and their causes in order to draw conclusions on the boiler's real performance. As seen in Misra et al. [29], the application of exergetic costs to a LiBr/H_2O vapour absorption refrigeration system enables an approximate optimum design configuration.

The CExC-method was also applied to analyse the resource consumption on a larger scale with different countries and societies [30], for example the United States [31] and China [32].

On a city scale, it was applied to compare energy scenarios in the smart city planning of Milan [33]. Waste heat [34] and low temperature district heat systems [35] were also investigated using exergy analyses. Krause et al. [16] carried out optimum power flow calculations for a MES to maximise its operational exergy efficiency. We did not find any recent literature where the CExC- or exergetic cost method was applied on municipal energy systems.

3. Methodology

In this work, we adapt the CExC-method to determine an exergy optimal design of a municipal MES. This requires modelling the energy system, and the assessment of energy as well as materials streams flowing in and out of the system. The optimal system design is reached when the CExC reaches a minimum. Therefore, we need a precisely formulated objective function and to model all the necessary constraints [21].

3.1. Cumulative Exergetic Consumption

CExC includes all exergetic losses and exergy destruction from raw materials or energy carriers to their final utilisation. Therefore, it quantifies the consumption of primary resources embodied in a product or service [23]. In an energy system, the exergy expenditures are stored in the energy imports, the materials necessary to build the infrastructure and the locally produced RES. RES and the imported energy carriers are converted to the desired form of energy to supply the load. Therefore, the services produced are both the load as well as the excess energy (Figure 1).

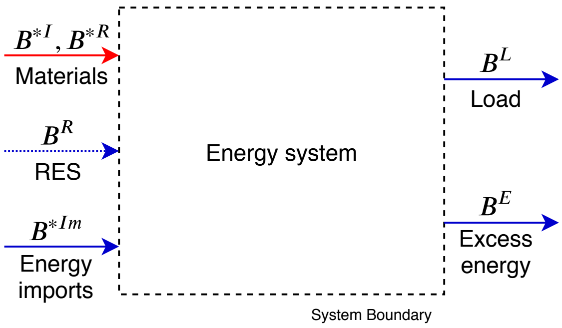

Figure 1. Material, RES, energy imports, load and excess energy flows over the system boundaries in an energy systems (source: own representation).

The imported energy flows may include renewable and nonrenewable sources. For the exergetic assessment of imported and exported energy following assumption are made [23]:

- Raw materials or energy carriers are attributed their reference exergy.
- Pre-treated materials or energy carriers are attributed an exergy content of their raw value and the exergetic expenses for the pretreatments.
- Any energy delivered to the load gets attributed its exergy content.
- Next to the energy produced to meet the load, excess energy might be created (Figure 1). If it can be further used, it is considered using its exergy content.

Therefore, for energy and material flows, we have to differentiate between their exergy content and their CExC. The exergy content B of an energy stream is the sum of its embodied physical, chemical, kinetic and potential exergy.

$$B = B_{pot} + B_{kin} + B_{ch} + B_{ph} \tag{4}$$

The "cumulative exergetic consumption" (CExC), B^*, of a stream is its exergy content, B, and all the exergy destruction, B_D; exergy losses, B_L; and exergetic expenses, B_{exp}, that occurred throughout the steps p of the production process PP of a stream. Any expenses are caused by irreversibilities within the production processes [19]. These can occur "directly or indirectly, in the extraction, preparation, transportation, pretreatment and manufacturing process" [21].

$$B^* = B + \sum_{p \in PP} \left(B_{D,p} + B_{L,p} + B_{exp,p} \right) \quad (5)$$

This means that the production route has an impact on the CExC of a product. The same product delivered by two different production processes can have a different CExC.

3.1.1. Unit Expenditures and Unit Content

In energy systems modelling, the descriptive variables are usually energy flows and the capacities of the installed infrastructure. Therefore, we use unit expenditures or unit contents to convert energy, E; materials, m; or capacities, C, to CExC or exergy. The unit expenditures describe the CExC per unit of energy, material or capacity. The conversion factor is called CExC-factor. The unit content describes the actual amount of exergy stored in a unit of energy. This conversion factor is therefore called exergy factor. The use of those conversion factors makes the CExC methodology applicable together with a broad range of energy system modelling tools.

The exergy factor r is used to convert energy to exergy. It is the proportion of exergy B in energy E:

$$r = \frac{B}{E} \quad (6)$$

The CExC-factor r^* is used to convert energy to CExC and describes the CExC per unit energy. It is the ratio between CExC B^* and energy E (Equation (7)). For materials the calculation is equivalent, but relative to a unit of mass m.

$$r^* = \frac{B^*}{E} \quad (7)$$

CExC for the different energy carriers can be taken from literature. In the cases where no data is available, the use of cumulative energy demand (CED)-values is also acceptable. This is applicable, because we only consider energetic resources in this paper. In such cases, CED and CExC-values have a comparable magnitude with a coefficient of determination of more than 99% [36]. Therefore we assume CED and CExC-values to be identical.

CExC B_I^* of the infrastructure units is incorporated in the materials necessary to build these conversion units, RES and storages. Therefore the infrastructure-CExC-factor r^* can be defined as the CExC per capacity unit C of a conversion unit, a RES, or a storage:

$$r^* = \frac{B^*}{C} \quad (8)$$

For some energy technologies, the CExC-factors are directly available in literature. As the lifetime of infrastructure units is usually longer than the investigated period in the model, CExC are only taken into account proportionally. Therefore, we can define the equivalent periodic CExC-factor r^{*p}. It expresses the CExC B^* over the investigated period per unit installed capacity C.

$$r^{*p} = r^* \cdot \frac{T}{T_{LT}} \quad (9)$$

If CExC-factors are not directly available in literature they can be calculated using data from existing infrastructure units. CExC over the lifetime T_{LT} of an infrastructure unit with the nominal capacity C_n can be calculated based on its material consumption m_m, and the respective material CExC-factors r_m^*. We assume linear relations between the capacity and the required materials, as well as between the investigation period T and the lifetime T_{LT}. Thus, the equivalent periodic CExC-factor expresses the CExC for one unit of capacity for a certain period of time:

$$r^{*p} = \frac{\sum_m r^*_m m_m}{C_n} \cdot \frac{T}{T_{LT}} \quad (10)$$

3.1.2. Example CExC for Domestic Heat from an Electric Resistance Heater

For district heating, we want to produce heat with an exergetic content of 0.2 (physical exergy calculated using Equation (2) and based on following assumptions; feed temperature 70 °C and reference temperature 0 °C). The installed electric heater shall have a capacity of 1 MW and an efficiency of 99%. In an investigation period of one year, the annually produced heat shall be equivalent to 2000 full load operating hours.

Electrical heater equivalent periodical CExC-factor: An electric heater with a nominal capacity of 10 kW and a lifetime of 15 a consists of 40 kg of steel. Steel has a CExC-factor of $1.75 \times 10^{-5} \frac{\mathrm{TJ}}{\mathrm{kg}}$. Material consumption of this boiler results in a CExC of 0.2 MW h. Therefore, using Equation (10) the equivalent periodic CExC for an electric heater is 1.3 $\frac{\mathrm{MW\,h}}{\mathrm{MW\,a}}$.

Electricity and heat CExC-factors and exergy factors: Even though the exergy content of electricity is 1, in Austria its CExC is 2.96. The annual heat production has an energy content of 1980 MW h and an exergy content of 396 MW h. The total exergetic expenditures (electricity and materials for the electric heater) add up to 5933.3 MW h per year. The exergy expenditures can be divided into 1.3 MW h for plant investment, 3920 MW h for pretreatment of the electricity and 2000 MW h for the electricity itself. Accordingly, the produced energy has a CExC-factor of 2.99, but only an exergy factor of 0.2.

For a plant with a given nominal capacity, the unit expenditures vary dependent on the annual full load operational hours. They include expenditures for the resistance heater and expenditures for the electricity. The latter ones consist of the expenditures, due to the consumption of physical exergy and the expenditures for the pretreatment. Pretreatment expenditures are those expenditures necessary to provide an energy carrier with its embodied physical exergy at the system boundaries. In this example, we assume that the pretreatment for electricity is constant. Also, the efficiency of the resistance heater is constant, which leads to a constant consumption of electricity per unit heat. Therefore the expenditures for physical exergy and pretreatment are independent of the full load operational hours and stay constant in Figure 2. For the expenditures from infrastructure investment it is different, because they only occur once during the investigation period. The more heat is produced with the resistance heater, the smaller becomes their share on the total unit expenditures (Figure 2). The cumulative unit expenditures for the electric heater with one full load operational hour are 4.3. For 8760 full load operational hours they decrease to 2.99. Then the share caused by plant investment is negligible.

3.2. CExC Minimisation of Multi-Energy Systems

The main objective in this paper is to design an energy system, which has minimum cumulative exergy destruction and exergy losses. We use a greenfield design approach, that means we do not consider existing energy infrastructure. A municipal energy system shall be designed for a given electricity and heat demand. On the one hand, exergy is needed in the form of materials to set up the physical infrastructure of the energy system. On the other hand, it is consumed in form of conventional energy carriers or RES to operate the system and supply the demand (Figure 3). In the case of high RES production, excess energy might be produced. The optimum system is reached, when the difference between exergy flowing into the system and exergy flowing out of the system gets a minimum.

A model must be set up which includes all relevant boundary conditions, but still leaves a certain degree of freedom for optimisation. For this task, we use the optimisation framework *oemof*, which is specifically designed for energy system optimisation. The model must allow several different supply routes using RES, conversion units (e.g., power plants, boilers, grids, etc.) and storages (e.g., batteries, hot water tanks, etc.). For these infrastructure elements, the used materials and their CExCs must be specified. The operational boundary conditions include the imported energy (e.g., electricity, natural gas, biomass, etc.) and RES potentials (e.g., wind, PV) and their CExC.

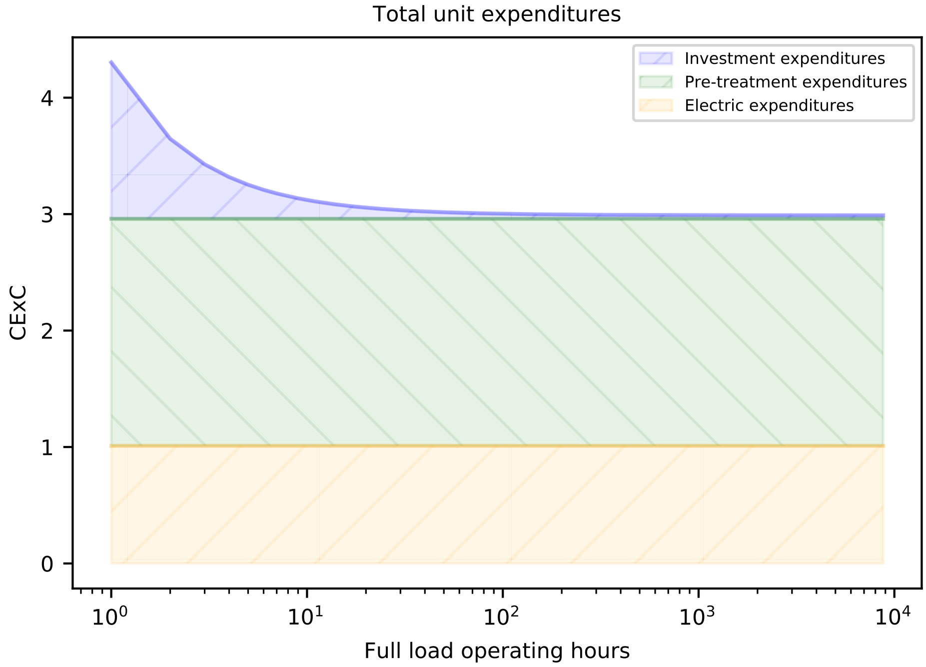

Figure 2. Total unit expenditures for investment, pretreatment and exergy consumption. (Source: own representation).

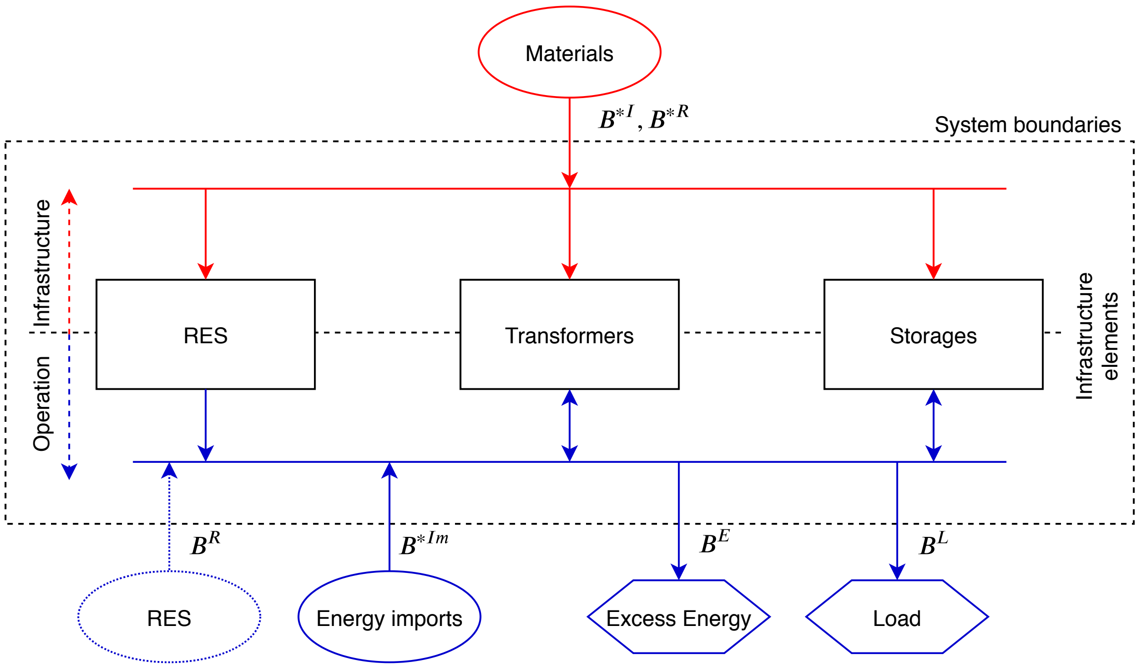

Figure 3. Cumulative exergetic consumption (CExC) flows, equivalent periodic CExC flows and exergy flows in an energy system. (Source: own representation).

3.2.1. *oemof*—Open Energy Modelling Framework

The Open Energy Modelling Framework (*oemof*) [37,38] is an open source framework for cross-sectoral and multi-regional modelling and optimising of MES. It can deal with multiple energy carriers, for example electricity, heat, biomass, natural gas, etc. In *oemof*, an energy system is represented by a graph, consisting of a set of edges and nodes. The edges are the logic links between the nodes, they describe the structure of the energy system. The nodes represent the technical components of the infrastructure. The components include all the main technical equipment of an energy system: sources, sinks, conversion units, grid elements and storages. The individual components can be connected via busses to each other.

Sources represent any imported energy, for example fuels, RES, natural gas and electricity from the grid. Sinks are used to model energy flows out of the energy system, for example, loads and electricity export. Energy conversion processes are described by conversion units, e.g., in power plants, boilers, etc. They can have multiple inputs (P^{in}) and multiple outputs (P^{out}) for a set of different energy carriers $\alpha, \beta, \ldots \in \Gamma = \{electricity, naturalgas, biomass, heat, \ldots\}$ and are described by their conversion efficiencies η [16].

$$\begin{pmatrix} P^{out}_{\alpha} \\ P^{out}_{\beta} \\ \vdots \\ P^{out}_{\omega} \end{pmatrix} = \begin{pmatrix} \eta_{\alpha,\alpha} & \eta_{\beta,\alpha} & \cdots & \eta_{\omega,\alpha} \\ \eta_{\alpha,\beta} & \eta_{\beta,\beta} & \cdots & \eta_{\omega,\beta} \\ \vdots & \vdots & \ddots & \vdots \\ \eta_{\alpha,\omega} & \eta_{\beta,\omega} & \cdots & \eta_{\omega,\omega} \end{pmatrix} \cdot \begin{pmatrix} P^{in}_{\alpha} \\ P^{in}_{\beta} \\ \vdots \\ P^{in}_{\omega} \end{pmatrix} \tag{11}$$

Energy storage is modelled using a differential energy balance between the state of energies SOE of two consecutive time steps (Equation (12)). It includes inflow and outflow conversion losses (η^{in}, η^{out}) and standby losses η^{loss} over a time step τ.

$$\Delta SOE = \eta^{in} \cdot P^{in} - \eta^{loss} \cdot SOE^{t-1} \cdot \tau - \eta^{out} \cdot P^{out} \tag{12}$$

Transmission and distribution infrastructure (e.g., power lines, district heat or natural gas pipelines) are modelled like conversion units with a conversion efficiency. They have the same input and output energy carrier. For any component a nominal value, minimum and maximum values as well as an actual value including a time series can be defined.

3.2.2. Objective Function

Cumulative exergy losses and exergy destruction become a minimum when the difference between expenditures and yields are a minimum. The expenditures include all the consumed exergy: for RES B^{*R}, for imported energy B^{*Im} and for the infrastructure B^{*I}. The yields include all the useful produces exergy: the load B_L, and any excess exergy B_E due to the variable production of RES.

As exergy is a potential compared to a reference state, this reference state must be selected carefully taking into account the objectives of the model. Therefore, we define the following assessment guidelines for the exergetic assessment of any inflow and outflow streams.

- All flows into the energy system get attributed their CExC-factor.
- All flows out of the energy system get attributed their exergy factor.
- Any form of energy becomes valuable as soon as it has a common usable and transportable form, therefore when it is secondary energy (e.g., electricity, district heat, natural gas, hydrogen or biomass). We do not assign the raw energy forms like solar irradiation or the kinetic energy stored in the wind speed any exergy. This is consistent with the international recommendations for energy statistics [39]

Based on these guidelines and the system boundaries specified in Figure 3, the objective function for the energy system over the time period T can be formulated as follows.

$$min(B^{*Im} + B^{*I} + B^{*R} - (B^{L} + B^{E})) \tag{13}$$

In *oemof*, the descriptive variables of streams and infrastructure units are power flows P and capacities C. With the help of time step τ power is converted to energy. CExC-factors and exergy factors described in Section 3.1.1 are used to convert these variables to exergies. All flows need to be summed up over the investigation period $T = \{t_{start}, \ldots t_{end}\}$.

All the imported energy flows must be converted to the CExC B^{*Im} for the period T:

$$B^{*Im} = \sum_{t \in T} \sum_{i \in Im} P_i^S(t) \cdot r_i^{*S}(t) \cdot \tau \tag{14}$$

Assessment of the outflows is analogous, but this time we use the exergetic value instead. The consideration of the outflows is only necessary, because we consider the excess energy E as valuable.

$$B^L = \sum_{t \in T} \sum_{j \in L} P_j^L(t) \cdot r_j^L(t) \cdot \tau \tag{15}$$

$$B^E = \sum_{t \in T} \sum_{k \in E} P_k^E(t) \cdot r_k^E(t) \cdot \tau \tag{16}$$

CExC calculation for all infrastructure elements I is based on the capacity C, and the equivalent periodic CExC $r^{*,p}$.

$$B^{*I} = \sum_{l \in I} r_l^{*p} \cdot C_l \tag{17}$$

According to guideline (3), RES R are different. Electricity P^R from RES is seen as an exergy expenditure and rated with its exergy factor. Operational upstream exergy losses, for example, from solar irradiation to electricity, are not taken into account. Next to the operational exergy expenditures, the infrastructure investment must also be considered. CExC is treated as analogous to the other infrastructure investments. Consideration of operational expenditures is necessary to avoid CExC-factors for electricity from RES, which are lower than its respective exergy factors.

$$B^{*R} = \sum_{t \in T} \sum_{m \in R} P_m^R(t) \cdot r_m^R(t) \cdot \tau + \sum_{m \in R} r_m^{*p} \cdot C_m \tag{18}$$

3.3. Result Evaluation

The major results are the installed capacities of conversion units, storages, RES, the energy consumption from the grids and the excess energy produced. We also calculate total CExC for energy inflows and the exergy outflows. To rate the operational performance of conversion units, the capacity factor c_l of any conversion unit l can be calculated:

$$c_l = \frac{\int_{t=0}^{t_{end}} P_l(t)}{P_{l,inst} t_{end}} = \frac{E_l^{out}}{E_l^{out,max}} \tag{19}$$

It compares the energy E_l^{out} a conversion unit produces during a certain period to the maximum energy $E_l^{out,max}$ a conversion unit could produce during this time.

The storage cycles c_s for any storage s show how often an energy storage is fully charged or discharged. It is the discharged energy E_s^{out} during a certain period divided by the installed storage capacity $C_{s,inst}$

$$c_s = \frac{\int_{t=0}^{t_{end}} P_s^{out}}{C_{s,inst}} = \frac{E_s^{out}}{C_{s,inst}} \tag{20}$$

4. Case Study

For our case study, we use the presented methodology in a greenfield approach to determine the optimum design of a municipal energy system. A greenfield approach means to model the energy system from the scratch. No existing infrastructure is considered. Energy loads, RES characteristics, exergetic indices and an available set of energy conversion technologies and storages are given. To account for the different shares of RES in the electricity from the grid, four different scenarios with different CExC-indices are evaluated. For any scenario a model is created in *oemof* and the results are discussed.

4.1. System Description

The medium-sized model city is located in a region attractive for wind power and PV installations, but has no potentials for run of the river hydro power or pumped hydro. Our case study focuses on municipal energy systems, therefore it considers electricity, process heat and domestic heat demand from the residential, commerce and public services sector. Industrial demand is not encompassed in our case study, because such consumers are mostly supplied by transmission grids and not by municipal distribution grids.

The energy system is connected to the electrical and natural gas transmission grids. RES potentials, biomass potentials and waste heat from an industrial process are available. For the sake of simplicity, we use an aggregated representation of the municipal energy system. All the individual conversion units, energy storages, RES, energy sources and energy loads of one kind are lumped together to a single one. This aggregation process is carried out according to the "cellular approach" [40]. To account for distribution grid losses, energy production and domestic consumption are modelled in two different regions or so called cells (Figure 4). Both are connected by electrical power lines and district heat networks.

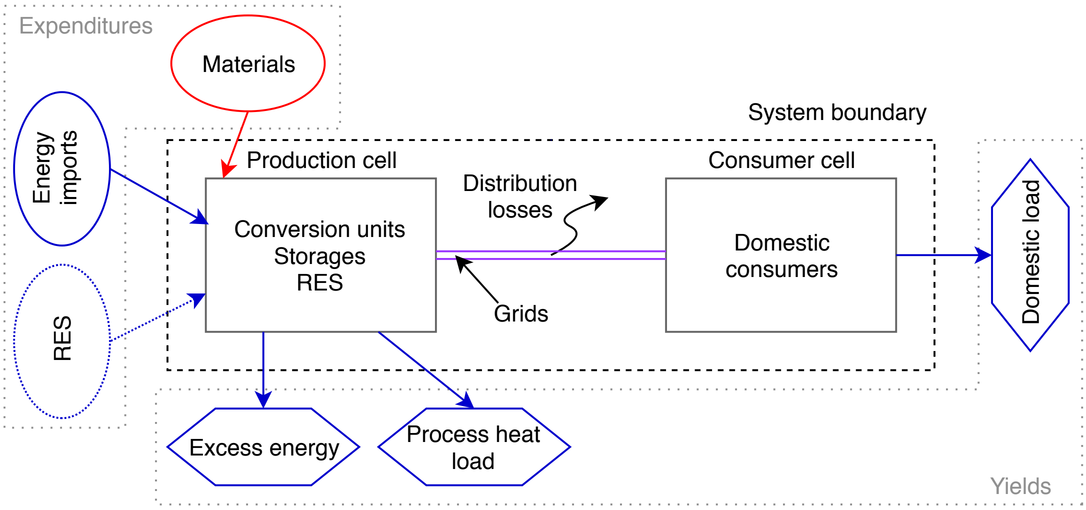

Figure 4. Two cell model with the exergy expenditure and yields. Conversion units, storages, renewable energy sources (RES) and the process heat load are located in the production cell. All domestic consumers are located in the production cell. (Source: own representation).

The values to be determined are the nominal capacities from conversion units, storages, RES as well as the imported energy and the excess electricity produced. Input parameters for the model are the loads, the available technologies, the maximum RES potentials and the possible conversion routes. In addition, CExC-factors and exergy factors must be provided for all specified technologies and energy carriers.

The electricity grid connection is bidirectional, that means that energy can be imported and exported. Even though in reality this is a single unit, in *oemof*, it is modelled using a source for imports and a sink for the excess electricity with a maximum connection power (Tables 1 and 2). Natural gas, waste heat and biomass are unidirectional, and therefore modelled using a source (Table 1). Natural gas and waste heat also do have a maximum capacity. The local biomass potential equals 22.5 GW h and must be fully exploited. Because biomass has no energy transport restriction like grid based energy carriers and can be easily stored, no maximum capacity is prescribed. CExC-factors for electricity, natural gas and biomass are taken from literature Table 1. Because there was no value available for waste heat, we estimated the CExC-factor based on its physical exergy using Equation (2) (assumptions: feed temperature 70 °C and reference temperature 0 °C).

Table 1. Energy sources: grid connection capacities and CExC-factors.

Imported Energy	Max. Capacity MW	CExC-Factor $\frac{\text{MW}}{\text{MW}}$
Electricity	60	$r^*_{el} = 2.96$ [41]
Natural gas	60	$r^*_g = 1.12$ [42]
Waste heat	3	$r^*_{wh} = 0.21$
Biomass		$r^*_b = 1.10$ [42]

Table 2. Excess energy: grid connection capacities and exergy factors.

Excess Energy	Max. Capacity MW	Exergy-Factor $\frac{\text{MW}}{\text{MW}}$
Electricity	60	$r_{el} = 1.00$

In our case study, we look at the domestic sector as well as at the businesses and commercial services sector. The annual demands specified in Table 3 include electricity, process heat, as well as domestic heating and hot water. Domestic heat has a temperature of 70 °C. Process heat is consumed by businesses and commercial services for the production of goods. The mean application temperature is assumed with 273 °C. Using Equation (2), this leads to the exergy factors specified in Table 3.

Table 3. Loads: annual demand, maximum power and exergy factors.

Load	Annual Demand GW h	Max. Power MW	Exergy Factor $\frac{\text{MW}}{\text{MW}}$
Electricity	55	11.9	$r_{el} = 1.00$
Domestic heat	90	38.2	$r_{dh} = 0.20$
Process heat	9	2.2	$r_{ph} = 0.50$

In *oemof*, all loads are modelled as sinks with fixed time series. We used the load profile generator *oemof demandlib* [43] to create load profiles with a resolution of 15 min from annual demand values . The required temperature data was retrieved from *renewables.ninja* [44,45] which uses the MERRA-2 data set. Exemplary for our model data of the year 2014 and the location of Eisenstadt (city in the eastern part of Austria; latitude: 47.84°, longitude: 16.54°) will be used. *oemof demandlib* uses standardised BDEW load profiles for modelling domestic and process heat time series [46,47] and electricity time series [48]. We assume that 30% of the heat is used in single family houses, 40% in multi family houses and the remaining 30% in small businesses, commerce and services. The domestic heat demand is calculated for windy conditions and includes the hot water consumption. 20% of the electricity is consumed by households, the remaining 80% by small businesses, commerce and services. The electric load profiles do not include any demand for hot water production, as this is already considered in the domestic heat load profiles.

All conversion units, storages, RES and the process heat load are located in the production cell. Energy conversion is modelled using Equation (11), energy storage using Equation (12). All the available energy conversion, energy storage and RES technologies in the model are listed in Tables 4–6. Note that the biomass boiler, gas boiler and resistance heater are made available for both the production of domestic heat and process heat. In addition, we assume that 20% of the high temperature process heat are waste heat, and can be further used for domestic heating. The specification parameters are conversion efficiencies, charge and discharge efficiencies, standby losses, maximum RES capacities, and equivalent periodic CExC per unit installed capacity. A detailed derivation (including all the references) of the equivalent periodic CExC for the individual units can be found in Appendix A. Normalised time series for PV and wind yields are retrieved from *renewables.ninja* using the same location and year as for the demand. Grid losses are modelled using transmission efficiencies and the networks do not have a restricting capacity (Table 7).

Using all the specified data, the objective function is composed according to Equation (13).

Table 4. Conversion units: considered conversion technologies.

Technology	Efficiency	Equivalent Periodic CExC-Factor $\frac{\text{MW h}}{\text{MW a}}$
Biomass boiler [49]	$\eta_{th} = 0.85$	$r^{*p}_{th} = 8.14$
Gas boiler [50]	$\eta_{th} = 0.95$	$r^{*p}_{th} = 6.83$
Heat pump [51]	$COP = 3$	$r^{*p}_{th} = 2.60$
PEM eletrolyser [52]	$\eta_{H_2} = 0.8$	$r^{*p}_{el} = 126.68$
PEM fuel cell [52]	$\eta_{el} = 0.8$	$r^{*p}_{H_2} = 126.68$
Resistance heater [53]	$\eta_{th} = 0.99$	$r^{*p}_{th} = 1.30$
Biomass CHP [54]	$\eta_{th} = 0.5$ $\eta_{el} = 0.35$	$r^{*p}_{el} = 81.5$
Gas CHP [55]	$\eta_{th} = 0.5$ $\eta_{el} = 0.35$	$r^{*p}_{el} = 24.34$

Table 5. Considered energy storage technologies.

Technology	Inflow Efficiency	Outflow Efficiency	Capacity Loss	Equivalent Periodic CExC-Factor $\frac{\text{MW h}}{\text{MW h a}}$
Battery storage [56]	$\eta^{in} = 0.86$	$\eta^{out} = 0.86$	$\eta^{l} = 10^{-8}$	$r^{*p}_{el} = 16.42$
Thermal energy storage [57]	$\eta^{in} = 0.99$	$\eta^{out} = 0.99$	$\eta^{l} = 2 * 10^{-4}$	$r^{*p}_{dh} = 4.19 \cdot 10^{-1}$
Hydrogen storage [58]	$\eta^{in} = 0.98$	$\eta^{out} = 0.98$	$\eta^{l} = 10^{-8}$	$r^{*p}_{H_2} = 1.24$

Table 6. Considered variable RES.

Technology	Max. Potential MW	CExC-Factor $\frac{\text{MW}}{\text{MW}}$	Equivalent Periodic CExC-Factor $\frac{\text{MW h}}{\text{MW a}}$
PV [59]	60	$r_{el} = 1$	$r^{*p}_{el} = 347.6$
Wind [60]	33	$r_{el} = 1$	$r^{*p}_{el} = 67.1$

Table 7. Transmission efficiencies of the energy grids.

Grid	Efficiency
Electricity	$\eta_{el} = 0.99$
Domestic heat	$\eta_{th} = 0.85$

Sensitivity Analysis with Respect to the Electricity Source CExC

Electricity from RES has a lower CExC-factor compared to today's prevalent thermal generation. This is because RES do not include the exergy destruction expensive conversion from chemical to thermal energy. Also the assessment guidelines (see Section 3.2.2, guideline three) support this, as the the produced electricity are the exergy expenditures and not the raw energy form like wind or solar irradiation. Therefore, the proceeding integration of RES into the future electric energy system will lead to decreasing CExC-factors for electricity from the grid. As these are relevant design parameters for the model, the different scenarios will lead to different optimum system designs.

An accurate value for future CExC-values cannot be determined at the present. Therefore, we will carry out calculations for four different scenarios, starting with the reference case SR. It describes the current state for the CExC-factor for electricity in Austria [41]. The following scenarios S1, S2 and S3 represent future electricity systems with higher shares of RES (Table 8). The other parameters stay the same in all four scenarios.

Table 8. Electricity CExC-factor for the sensitivity analysis.

	SR	S3	S2	S1
CExC in $\frac{MW}{MW}$	2.96	2.00	1.50	1.25

4.2. Results

The high exergy expenditures for imported electricity in the reference case SR lead to the highest total exergy expenditures (Figure 5). They also make investments into conversion units, storages and RES worthwhile. This leads to the higher expenditures for investment and RES as well as fewer energy imports. The large installed capacities of variable, non-dispatchable RES also generate more excess electricity.

At times when the grid connection is not a limiting factor, the CExC-factor for electricity from the grid determines the maximum unit expenditures for local electricity generation. The unit expenditures are influenced by the CExC-factor of the used energy carrier, the investment expenditures, the efficiency and the capacity factor (compare to Figure 2). Only technologies which comply with this limit will be selected, otherwise the energy will be drawn from the grid. Therefore, the lower CExC-factors in S3, S2 and S1 will not allow for an infrastructure investment as extensive as in SR. This leads to reduced total exergy expenditures and a shift from infrastructure investment to energy imports. Due to the lower installed RES capacities, excess electricity also decreases in those scenarios.

The following sections provide further details on installed capacities and operation of conversion units, RES and storages for all four scenarios. Afterwards the operational exergy expenditures and exergy yields are presented, followed by a discussion of the results.

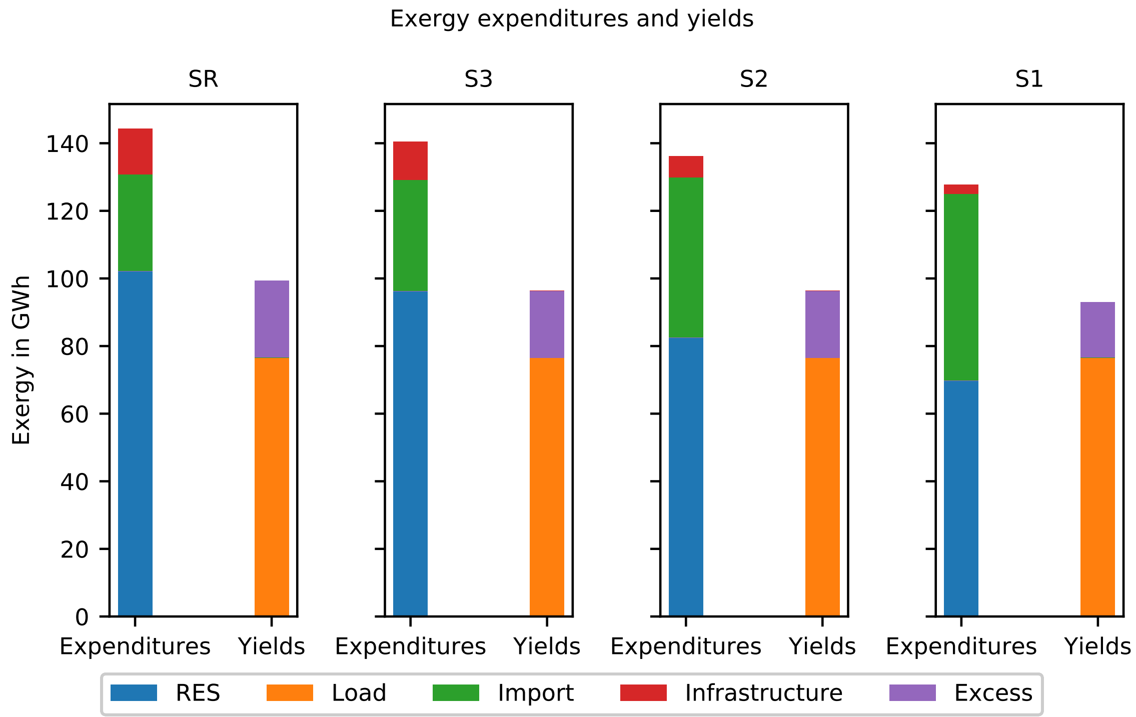

Figure 5. Exergy expenditures and yields of the different scenarios. Expenditures include CExC from energy sources, RES, and for RES and infrastructure investment. The yields include the exergy for the load and excess exergy. (Source: own representation.)

4.2.1. Infrastructure Capacities and Expenditures

The capacities and the corresponding CExC from installed conversion units and RES are shown in Figure 6. Available technologies described in Section 4.1 that have not been selected for deployment, are not shown in the results. All the displayed capacities relate to the power produced (e.g., heat for the heat pump and boilers, electricity for RES). In the case of the CHP, which produces heat and electricity, the nominal electrical output is displayed.

Compared to the other conversion units, the high installed capacities of heat pumps and wind are apparent. PV and CHP capacities rise with an increase in the CExC-factors in the scenarios. While wind power is expanded to its maximum potential in all scenarios, PV never uses its maximum potential. A PEM electrolyser and fuel cell are installed only in SR. Biomass boilers and gas boilers are only used to supply the process heat load, but not for domestic heat. Even though RES do not have the highest installed capacities, their CExC exceeds the expenditures for conversion units by several orders of magnitude in all scenarios.

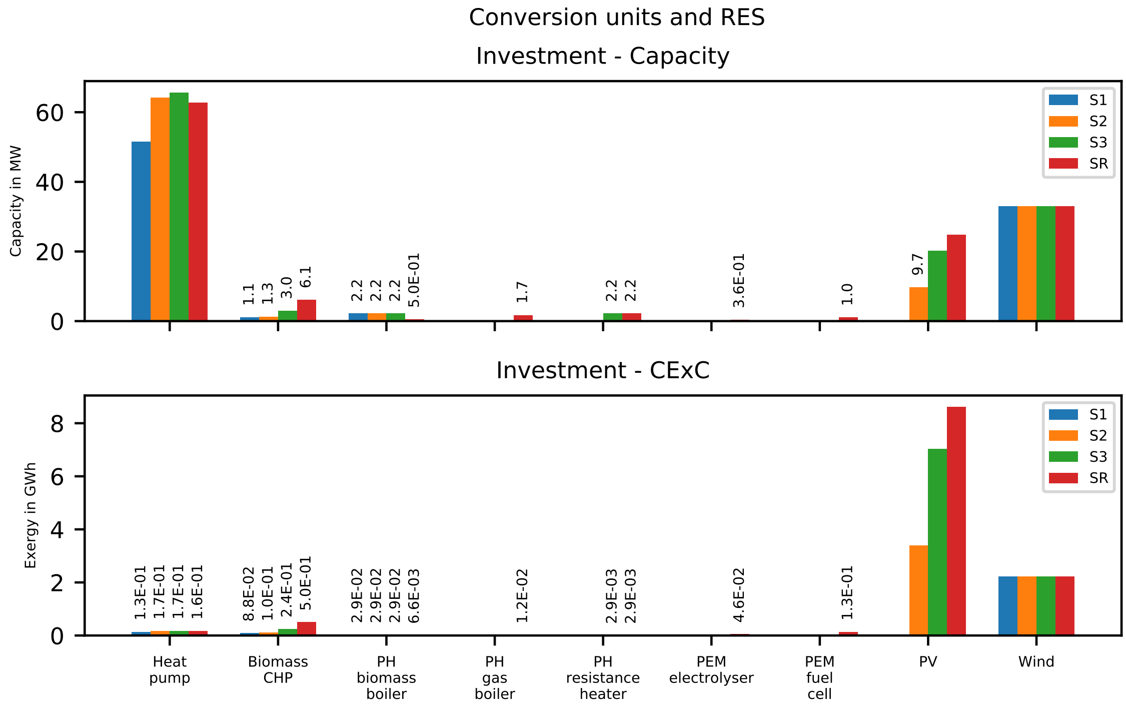

Figure 6. Calculated optimum conversion unit capacities and the corresponding CExC (Source: own representation).

All the different conversion units and storages are operated exergy efficiently and depending on the overall composition of the system. Even though we used 15-minute mean values in our model, we use daily mean values to present the results for unit operation in Figure 7. This provides a better visualisation of the long-term results. In this case, for the period of a whole year.

The heat pump provides domestic heat all year long except for the summer month. The biomass CHP operates mainly during times with a high heat demand and a low PV yield. At the same time, process heat in S3 is produced by a biomass boiler, and in SR, it is produced by a biomass and gas boiler. In the complementary times, the process heat is provided by a biomass or gas boiler and a resistance heater, which is operated with excess electricity from PV or wind (Figure 7). In S1 and S2, high temperature heat is provided by biomass boilers and resistance heaters. The electrolyser is predominately operated in the second half of summer and in autumn. The conversion back to electricity takes place at the beginning of the year and in the second half of the year.

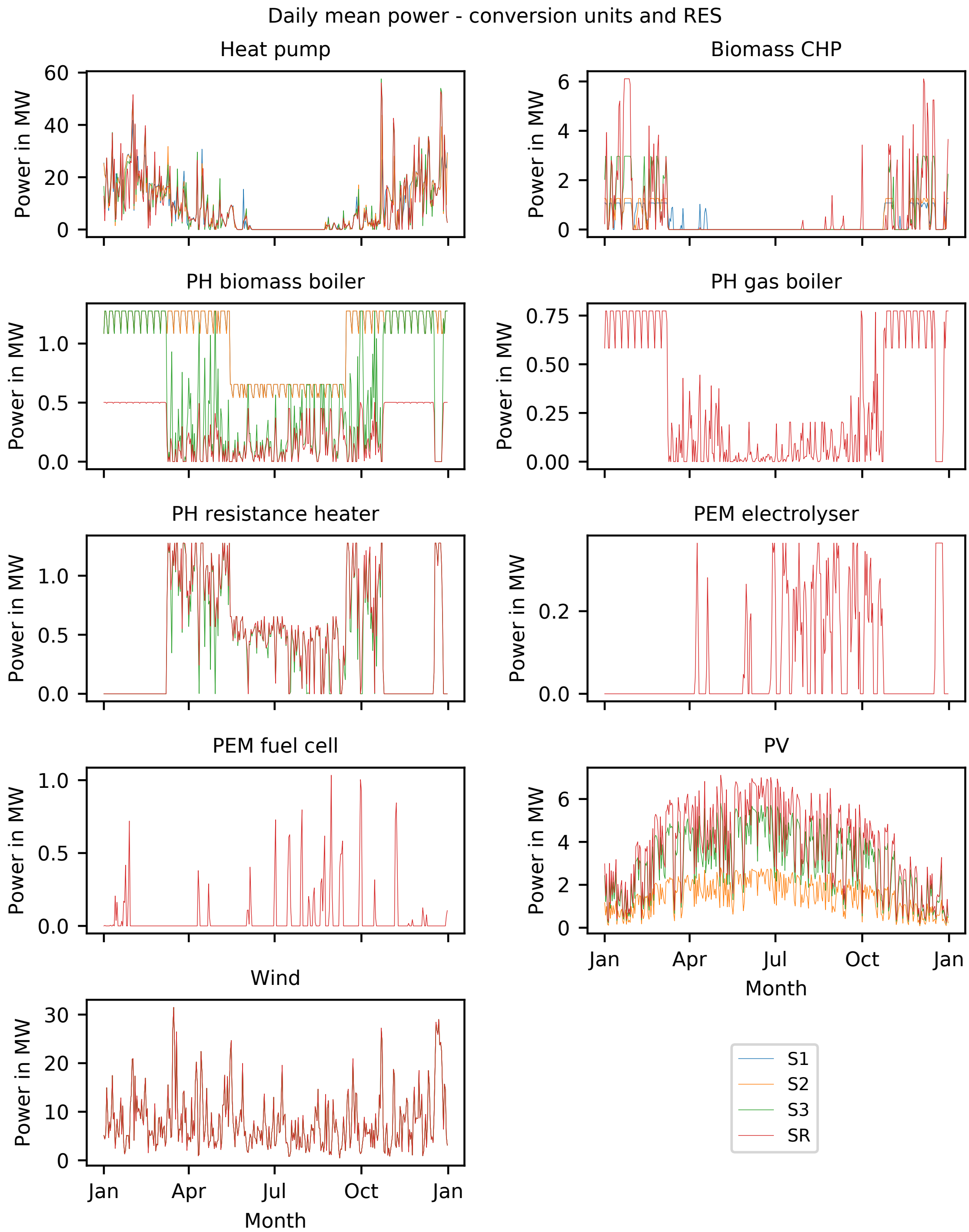

Figure 7. Daily mean power of the conversion units and RES. (Source: own representation).

The more different conversion units available, the lower the capacity factors (Table 9), which are calculated according to Equation (19). Exceptions are small scale units with dedicated base-load operation, for example, the process heat biomass boiler in SR. Because of the major seasonal component of domestic heat and hot water demand, the capacity factors for the production units are restricted by the shape of the load profile. The same applies for the electrolyser and the fuel cell. They are part of the long term H_2 storage and only one can operate at a time.

Table 9. Capacity factors of conversion units and RES.

	S1	S2	S3	SR
Heat Pump	16.6	13.4	12.9	13.2
Biomass CHP	27.5	23.5	15.9	10.0
PH biomass boiler	46.4	46.4	27.0	51.4
PH gas boiler	-	-	-	18.1
PH resistance heater	-	-	19.4	20.7
PEM electrolyser	-	-	-	20.0
PEM fuel cell	-	-	-	5.2
Wind	24.1	24.1	24.1	24.1
PV	14.9	14.9	14.9	14.9

The installed storage capacities are shown in Figure 8. The thermal storage capacity is several orders of magnitude larger than the battery and the hydrogen storage. Even though, the CExC for batteries and thermal energy storages are of a comparable magnitude. Hydrogen storage only makes exergetically sense in scenario SR. Remarkable is the vast increase of battery and thermal energy storage increase between the scenarios S2 and S3.

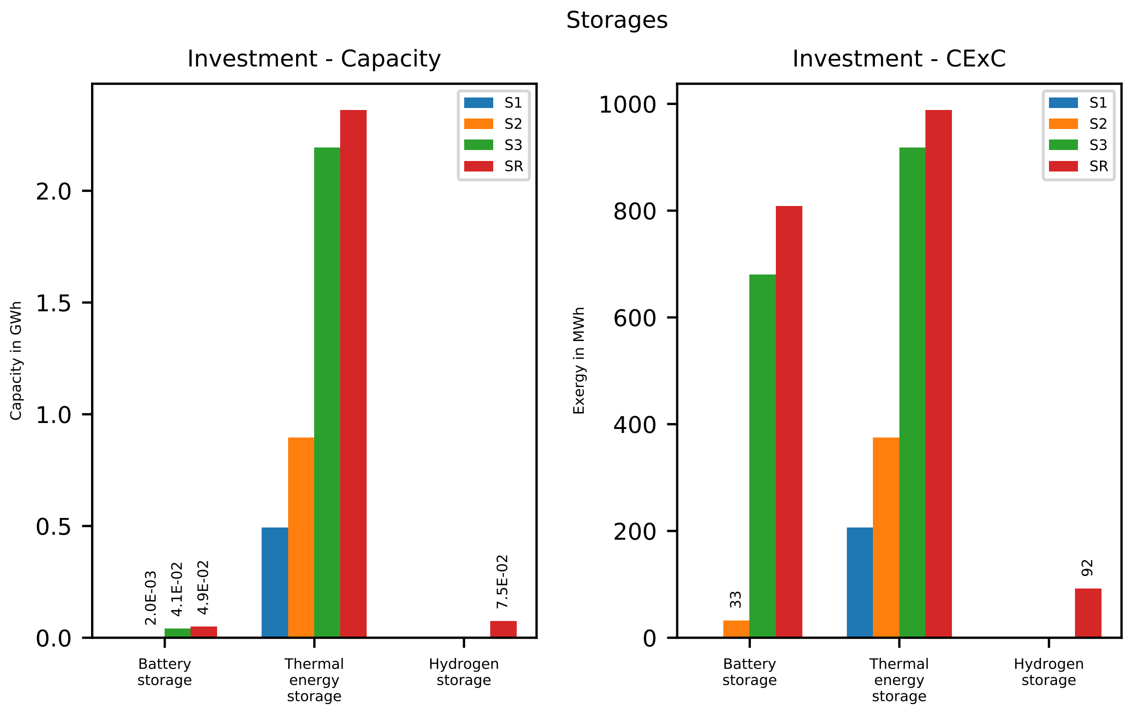

Figure 8. Calculated optimum storage capacities and the corresponding CExC. (Source: own representation).

The storage facilities are operated exergy-efficiently to bridge the gap between variable RES production and demand. Figure 9 shows the daily mean state of energy. With the help of the discrete Fourier transform (DFT), the state of energies time series can be decomposed into their individual periodical components. The results in Figure 10 show the amplitude and the numbers of cycles per year. Components which are smaller than 15% of the maximum amplitude are removed from the plots.

In all four scenarios, the battery shows the highest states of energy during spring and autumn. During summer, the storage cycles are shorter, but the mean states of energy are also lower (Figure 9). The DFT analysis shows clearly defined annual (one cycle per year) and daily cycles (365 cycles per year) in all three scenarios in which a battery is installed. The thermal energy storage is mainly used during the heating season with similar peak states of energy in the beginning and the end of the year.

Exceptions are S3 and SR, where the peaks in autumn are more than twice as high compared to the spring. In all four scenarios, the amplitude of annual cycle is clearly dominant. The amplitude of this annual cycle is all the more significant with larger installed storage capacities. The hydrogen storage starts to get charged in July to shift electricity from the sunny periods to autumn and winter. Its state of energy has significant annual and biannual cycles.

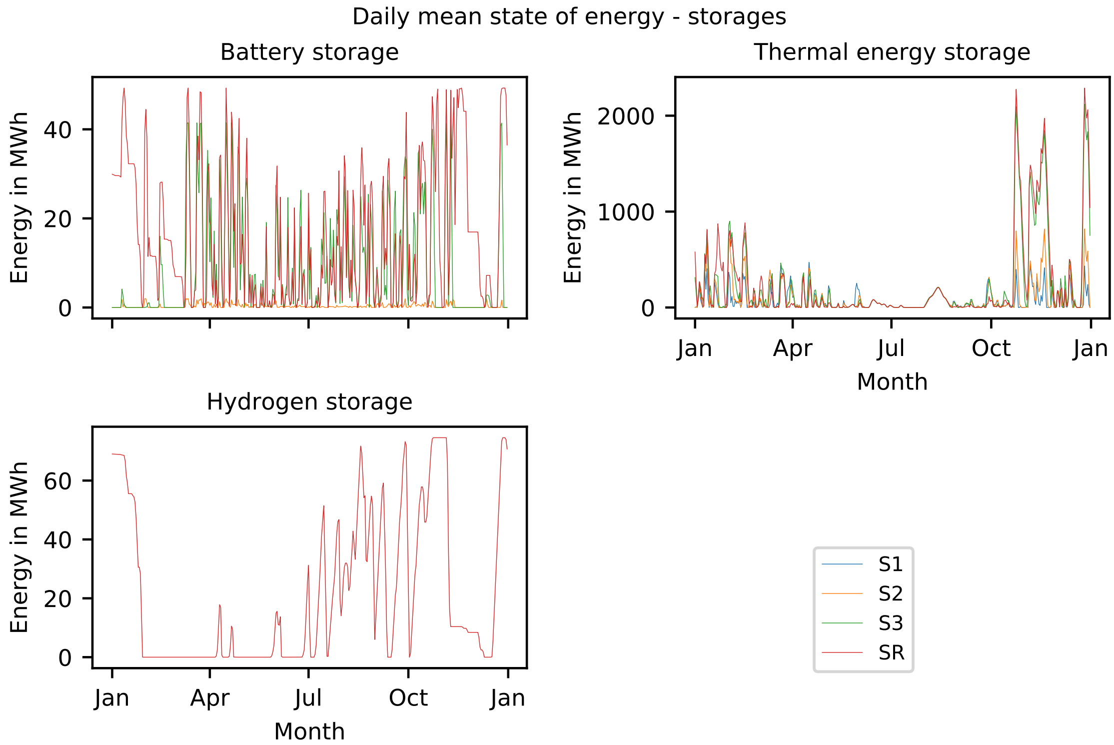

Figure 9. Daily mean states of energy. (Source: own representation).

The full cycles that a storage can achieve depends on load and production time series, as well as the size and purpose of a storage (Table 10). The battery in S2 has more than twice as many full cycles compared to the ones in S3 and SR. The thermal storage has the most utilisation during the heating season and is barely utilised in summer. Although the thermal storage peak states of energies are in the same order of magnitude for spring and autumn in S1 and S2, they are more than twice as high in autumn for scenarios S3 and SR. Excess electricity is used by heat pumps to shift the excess energy from PV over longer periods to times with higher demand and less supply. This requires higher storage capacities where large shares of the total capacity are not very often used. This and the great demand difference between summer and winter leads to significantly less storage cycles compared to the battery. Even though the hydrogen storage is a seasonal storage technology, it has 8.4 full storage cycles per year.

Table 10. Full storage cycles per year.

	S1	**S2**	**S3**	**SR**
Battery storage	-	140.1	68.6	67.2
Thermal energy storage	37.7	22.2	11.5	10.3
Hydrogen storage	-	-	-	8.4

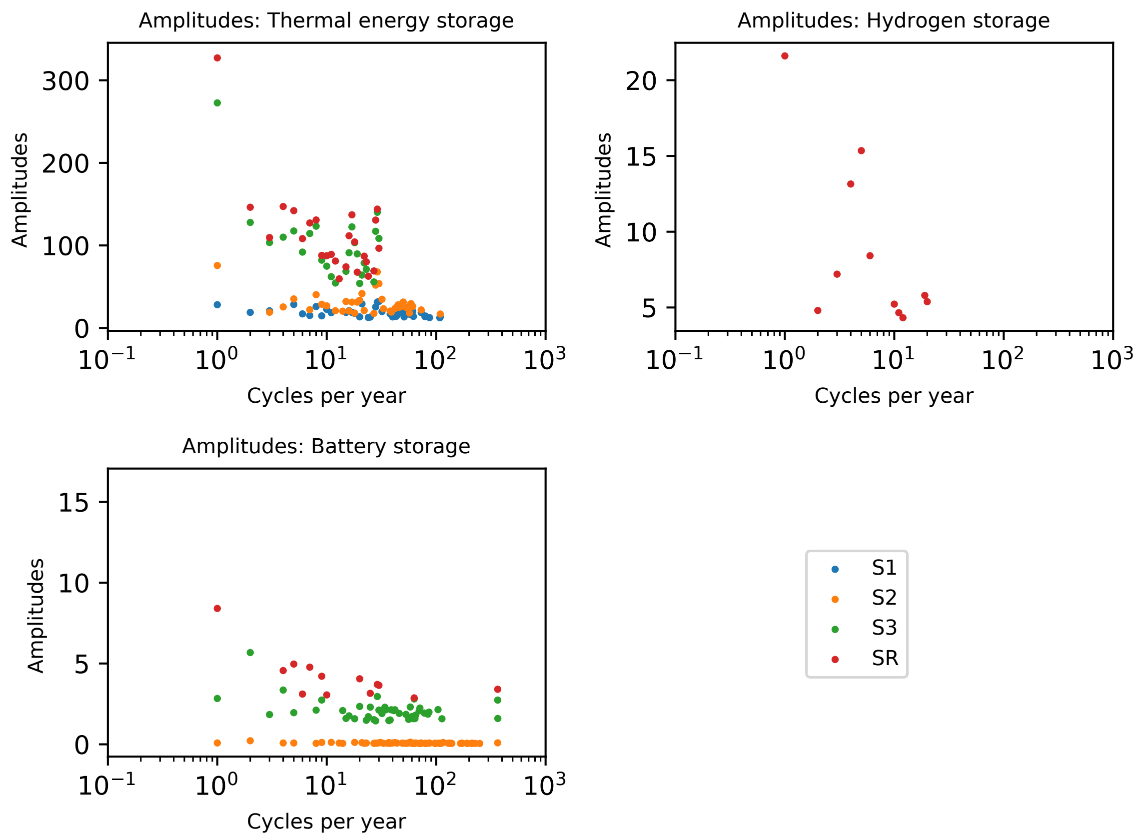

Figure 10. Periodical components of the state of energy. (Source: own representation).

4.2.2. Energy Imports, Excess Energy and Loads

Figure 11 shows annual energy and exergy loads, excesses, imports and the RES production. Loads, waste heat imports, biomass imports and electricity production from wind stay constant in all four scenarios. Imported electricity and natural gas, PV production and excess energy vary across scenarios with the CExC-factor for imported electricity. The higher the CExC-factor, the higher are PV-production and excess electricity, and the lower are the electricity imports. In scenario SR where the CExC-factor is the highest, no electricity is imported, but natural gas. Also, it is clearly visible that the exergy content of domestic heat is low when comparing annual energy and exergy loads of the domestic heat.

Figure 12 shows the daily mean power for loads, electricity excess, and energy imports. Electricity and process heat loads mainly fluctuate over days and weeks, the annual variations are secondary. For the domestic heat load it is different. Its major annual fluctuation is caused by its strong temperature dependency. Biomass and gas imports are the highest when the heat load is highest as well. The waste heat is consumed to its maximum extent, except for short periods in summer.

Daily average values for electricity imported from the grid show a high variability. Although there are days with very little to no consumption, those days can be followed by peaks up to an average of 12 MW. The highest daily average values for electricity drawn from the grid occur during the winter months. In the summer months, those peaks drop to half of those values for S1 (Figure 12). This spread increases with increasing electricity CExC-factor until no electricity is consumed in SR. Excess electricity is produced between March and November, and in winter in case of high wind production. For SR Figure 12 shows that the exported electricity decreases from its peak in spring until autumn.

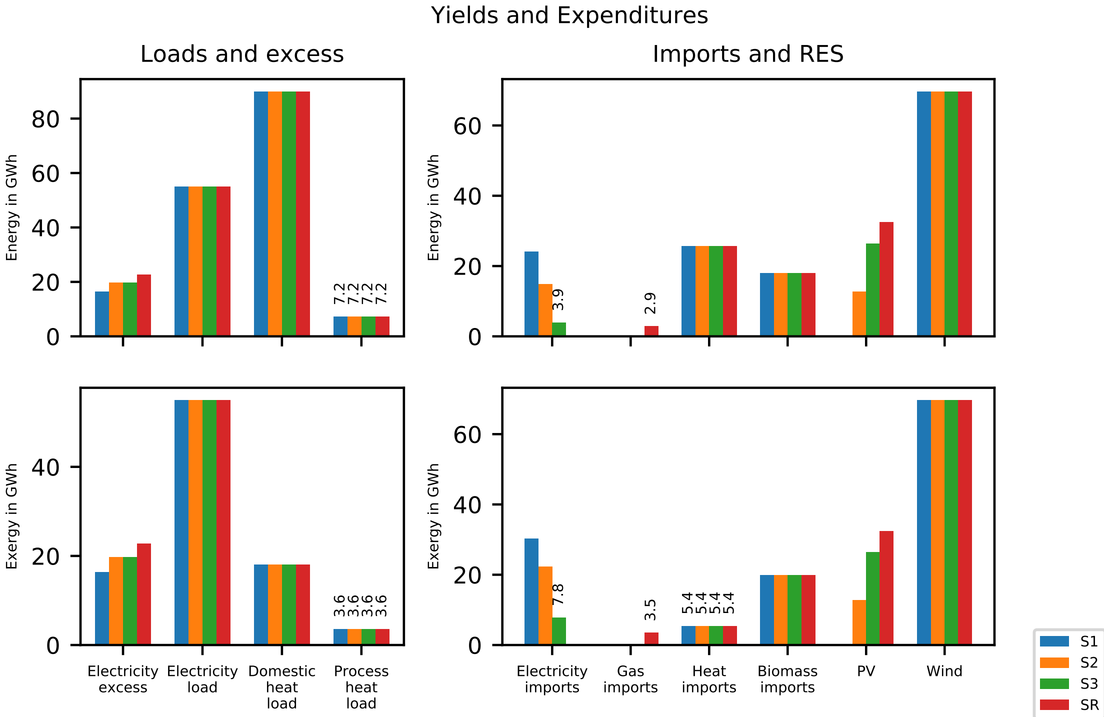

Figure 11. Energy sources and energy load, and the corresponding CExC, exergy load and excess exergy. (Source: own representation).

4.2.3. Result Discussion

Compared to imported energy, RES can provide energy for lower expenditures, but their fluctuating production does not necessarily meet the current demand. This gap must be compensated by energy drawn from the grid, or additional local power plants and storage facilities. Between the two options, the choice depends on unit expenditures for energy imports, and the investment as well as operational expenditures for conversion units and storage facilities. The unit expenditures of the imported energy carriers limit the maximum unit expenditures of local energy production, as long as there is no import capacity restriction. The local unit expenditures for an energy carrier include expenditures for conversion units and storages, and for exergy destruction and losses. The results reflect this context in higher total expenditures and a shift from operating to infrastructure expenditures in scenarios with higher CExC factors for imported electricity. Therefore, of all the scenarios, SR has the highest installed capacities of RES and conversion units (Figure 6), and is the only one where a long-term hydrogen storage makes sense (Figure 8).

In our model, electricity imports can be seen as unrestricted, because the maximum load is well below the maximum grid capacity (Tables 1 and 3) This means that local production is only preferred if it has lower expenditures than the energy imports. In the case of excess electricity from RES, it can be stored locally for later use or it can be returned to the grid. For a useful storage investment, unit expenditures for electricity from RES and the battery must be lower than for imported electricity. The yield for electricity export must be also considered. This is the context that leads to the installed capacities of RES and storages. In all four scenarios, the wind power potential is used to its maximum. No PV is used in S1, but it rises up to 24.8 GW in SR, which is equal to 99.1% of the available potential. The higher CExC-factors for imported electricity make PV installations and battery storage practical in S2, S3 and SR. Long term storage using power to gas is exergetically only reasonable in SR.

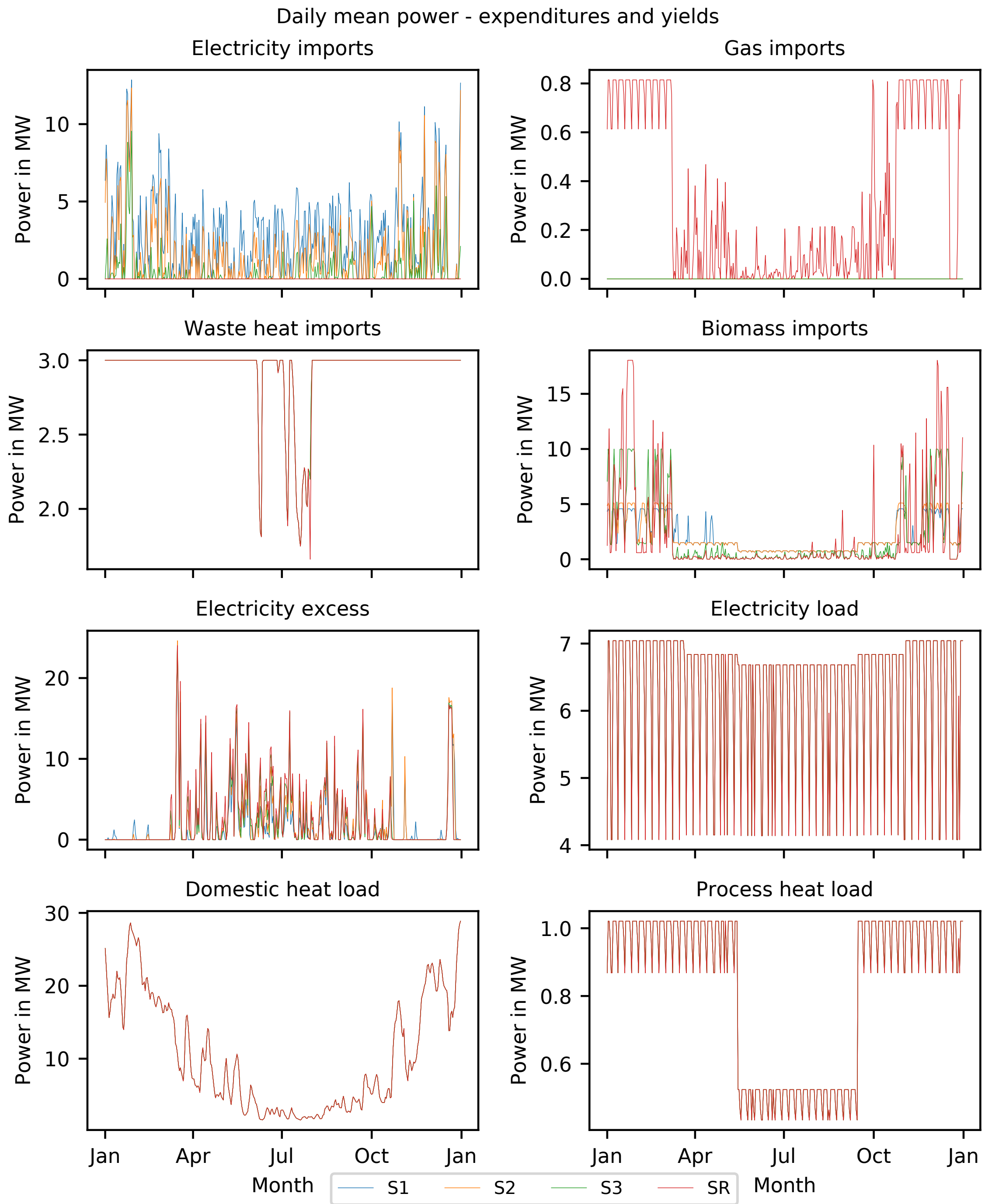

Figure 12. Daily mean power of the operational expenditures and yields. (Source: own representation).

For domestic heat, the situation is different. The maximum waste heat import power of 3 MW covers only 8% of the maximum domestic heat load. The remaining heat will be provided by the plants with the lowest total unit expenditures, under the consideration that the local biomass has to be used. The biomass is used in a biomass CHP which is mainly operated in times where the heat demand is high and PV yields are low. Heat pumps together with thermal energy storage cover the rest.

From S2 to S3 the CExC-factor and therefore the unit expenditures for electricity imports rises from $1.5\,\frac{\mathrm{MW}}{\mathrm{MW}}$ to $2\,\frac{\mathrm{MW}}{\mathrm{MW}}$. This results in an increase of the battery storage capacity from 2 MW h to 39.5 MW h and of the thermal energy storage from 895 MW h to 2193 MW h. Apart from the two scenarios, there are no others where the increase in storage capacity is so large. As already discussed above, raising the limiting unit expenditures for electricity imports allows for higher total unit expenditures. The increase can be totally attributed to the infrastructure expenditures, because the operational unit expenditures stay constant. This tolerates lower capacity factors or annual storage cycles. Due to the fact that the investment unit expenditures follow a reciprocal function (see Figure 2), such a vast increase of the storage capacities between these two scenarios is possible.

5. Conclusions

The method of the CExC minimisation has proved to be applicable to energy systems planning and operation. The usage of CExC-factors makes the methodology applicable to a wide range of modelling tools. Aggregation concepts like the "cellular approach" [40] allow for the deployment on different spatial scales with different levels of accuracy. Even though we presented a greenfield design approach, it is also well suited for brownfield design approaches, for unit commitment, and even for optimal power flow calculations.

The major point of the overall results is that a well linked electricity and heat sector, using heat pumps and thermal energy storage, can enable a resource efficient supply while providing the necessary flexibility for integrating variable RES at the same time. Co-generation of heat and electricity is beneficial to separate production. The second point is the consideration of the load collective of the different plants. Although the operational efficiency of one technology might be higher compared to another, its high investment CExC makes this technology more costly in cases with low annual capacity factors.

In general, for the same rated power an exergy efficient plant will be larger compared to a less exergy efficient one (e.g., compare the sizes of compression and absorption chillers.) [61]. This is because exergy efficient plants have to operate with lower driving potentials, which leads to larger plants and therefore to higher CExC for the plant investment. For example, for the same heat transfer capacity, heat exchangers with higher temperature differences between the hot and the cold fluid need smaller exchange surfaces than heat exchangers with lower temperature differences. This means that operational expenditures shift to investment expenditures. Therefore, exergy efficient plants need higher capacity factors than less exergy efficient plants to reach the same unit expenditures. The variability of RES requires additional storages and dispatchable back-up plants with high capacities. This will lead to low annual capacity factors for the individual plants, which contradicts the use of exergy efficient technologies. In such cases, investment expenditures might not be negligible any more compared to the operational expenses. The CExC methodology takes both discrepancies into account and supports finding an optimal solution.

Although exergy factors for energy streams can be unambiguously calculated by thermodynamic laws, we know that the CExC-factors for the inflows do not have such a high degree of accuracy and are subject to uncertainties. The influence of the investment CExC should also not be overestimated, because in none of the scenarios it exceeds 10% (Table 11). For a comparison, the conversion losses (exergy losses and destruction within the energy system) range from 21.8% to 25.1%. A sensitivity analysis of the investment CExC of the individual plant can help to get a better understanding of their implications.

Table 11. Share of investment and conversion losses on the total CExC input.

	S1 %	**S2** %	**S3** %	**SR** %
Investment	2.1	4.6	8.0	9.4
Conversion losses	25.1	24.7	23.4	21.8

Most of the current applications of technical exergy analyses differ in two points: the assessment of consumed energy carriers and materials according their physical exergy or CExC, and the use of either an energy-based or power-based perspective. Energy-based means that only the energy consumption over a certain period of time (usually one year) is considered for analysis. A power-based perspective also takes into account the variation in energy consumption over time [11].

Both of the above-stated points can have significant impacts on the relevance of the results. The use of physical exergy as an evaluation criterion could favour energy sources with high exergy losses outside the system boundaries over those produced internally. A power-based approach, as we use it in our work, is important for the sizing of system components and, in the case of involved storages, for considering their operational impact. Applications using physical exergy and a power-based approach mainly concern individual industrial processes or plants to identify internal exergy destruction and losses [5]. Energy-based perspectives are used above all when larger energy systems, in which the individual processes are no longer comprehensible, are considered over a longer period of time. Some consider only the flows of energy carriers, others include both energy and material flows [30].

Municipal energy systems lie between these two extremes. Our approach with using CExC-minimisation for design and operation of such energy systems helps to overcome this gap. It contributes to the identification of the location and magnitude of high exergy destruction and losses within the system. However, the use of CExC shows whether these are better treated within or outside the system boundaries. Including the materials for the plant investment permits optimum sizing of the plants for the respective load collective.

In future modelling applications, there are several improvements that can be made:

- A better representation of the **electric grid connection**. In this paper, we use a constant CExC-factor for electricity from the grid. We assume grid availability for feed in and drawing energy all the time. This might not be true for future applications. The CExC-factor might vary over the day and the seasons. There might also be shortages or congestion in the transmission grid.
- The **spatial dimension**. The current model does not account for the distribution of energy. Restricted energy transport capacities and the unavailability of network coverage in some areas, especially heat and gas grids, will lead to different results. The network restrictions can be modelled using total transfer capacities, or if more detail is necessary, power flow models.
- Include further **technologies**. Currently, only a basic set of conversion technologies (Table 4), RES (Table 6), and storages (Table 5) is used in the model. Possible additional technologies are demand side management; absorption heat pumps; solid oxide fuel; and electrolysis cells, pumped hydro, tidal energy, etc. The use of storage capacities inherited in heat and gas networks can also support the integration of RES.
- Include additional **sectors**. Currently, only the residential sector, and commercials, private and public services sector are considered in the model. Together they consume 34.3% of Austria's final energy demand. The other large consumers are the industry sector with 29.3% and the transport sector with 34.4%. An incorporation of both sectors into a municipal energy system model can support in finding an exergy efficient design. A better model of industrial processes can lead to synergies between industrial and municipal energy systems. In addition, a shift to electric mobility will increase electricity demand and include a high DSM potential.

Author Contributions: The authors contributed as following to the manuscript: conceptualisation, L.K. and T.K.; methodology, L.K.; software, L.K.; resources, L.K.; writing—original draft preparation, L.K.; writing—review and editing, T.K.; visualisation, L.K.; supervision, T.K.; project administration, T.K.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: I want to thank my colleague Philipp for all the support creating the plots.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CED	cumulative energy demand
CExC	cumulative exergy consumption
CHP	combined heat and power
DFT	discrete Fourier transform
OECD	Organisation for Economic Co-operation and Development
RES	renewable energy sources
A	anergy
B	exergy
B^*	CExC
c_c	capacity factor
c_s	annual full storage cycles
E	energy
h	enthalpy
η	efficiency
m	mass
P	power
r	exergy factor
r^*	CExC-factor
r^{*p}	equivalent periodical CExC-factor
s	entropy
t	time series
T	time period
τ	time step
ϑ	temperature

Appendix A. Equivalent Periodic CExC

Equivalent periodic CExC-factors for infrastructure units are calculated using Equations (9) or (10). All data regarding RES, conversion units and storages is available in Tables A1–A5. Material CExC-factors are composed of exergy demand for RES, non-RES and other energy sources and can be found in Table A6.

Table A1. CExC-factors and lifetime for PEM fuel cell and electrolyser.

	CExC-Factor $\frac{\text{MW h}}{\text{MW}}$	Lifetime a
PEM fuel cell [52]	1900.2	15
PEM eletrolyser [52]	1900.2	15

[a] Because PEM electrolysis and fuel cell technology are comparable, we assume the same CExC-factors for both.

Table A2. CExC-factor and lifetime for the Li-ion battery.

	CExC-factor $\frac{\text{MW h}}{\text{MW h}}$	Lifetime a
Battery storage [56]	328.3	20

Table A3. Capacity, lifetime and material data for conversion units—part I.

	Capacity kW	Lifetime a	Steel kg	Concrete kg	Organic PVC kg	HDPE kg
Gas boiler [50]	10	15	200		10	
Gas CHP [55]	250	15	5000	50,000		
Wind [60]	500	20	50,000	300,000		7500
Biomass CHP [54]	800	20	48,000	800,000		

Table A4. Capacity, lifetime and material data for conversion units—part II.

	Capacity kW	Lifetime a	Steel kg	Copper kg	Silicon kg	Aluminium kg
PV [59]	300	30	60,000	1500	30,000	5400
Resistance heater [53]	10	15	40			
Heat pump [51]	10	15	80			
Biomass boiler [49]	50	15	1250			

Table A5. Capacity, lifetime and material data for storages.

	Capacity kW h	Lifetime a	Steel kg	Concrete kg	Organic PVC kg	HDPE kg
Thermal energy storage [57]	466	50	970		230	
Hydrogen storage [58]	1	50	13			

Table A6. CExC-factors of the used materials of the considered conversion units and storages.

Material	CExC-Other TJ/kg	CExC-Renewable TJ/kg	CExC-non Renewable TJ/kg	CExC TJ/kg
Steel [62]	2.66×10^{-6}	1.15×10^{-8}	1.49×10^{-5}	1.75×10^{-5}
Organic PVC [63]	-5.7×10^{-7}	4.6×10^{-6}	1.36×10^{-5}	1.76×10^{-5}
Concrete [64]	5.18×10^{-8}	1.42×10^{-7}	4.62×10^{-6}	4.81×10^{-6}
HDPE [65]	2.82×10^{-7}	1.03×10^{-7}	1.18×10^{-5}	1.22×10^{-5}
Aluminium [66]	3.24×10^{-6}	3.16×10^{-5}	1.05×10^{-4}	1.40×10^{-4}
Copper [67]	1.80×10^{-6}	3.70×10^{-6}	3.38×10^{-5}	3.93×10^{-5}
Silicon [68]	7.63×10^{-6}	5.05×10^{-5}	2.55×10^{-4}	3.13×10^{-4}

The results for conversion units and RES are presented in Table A7. The results for the storages in Table A8.

Table A7. Equivalent periodic CExC for conversion units and RES technologies.

	Equivalent Periodic CExC $\frac{\text{MW h}}{\text{MW a}}$
Gas boiler	6.83
Gas CHP	24.33
Resistance heater	1.30
Heat pump	2.60
Wind	67.06
PV	347.6
Biomass boiler	8.13
Biomass CHP	81.50
PEM fuel cell	126.68
PEM electrolyser	126.68

Table A8. Equivalent periodic CExC for storage technologies.

	Equivalent Periodic CExC $\frac{\text{MW h}}{\text{MW h a}}$
Battery storage	16.42
Thermal energy storage	0.42
Hydrogen storage	1.24

References

1. Geyer, R.; Knöttner, S.; Diendorfer, C.; Drexler-Schmid, G. *IndustRiES: Energieinfrastruktur für 100% Erneuerbare Energie in der Industrie*; Klima- und Energiefonds der österreichischen Bundesregierung: Wien, Austria, 2019.
2. Sejkora, C.; Kienberger, T. Dekarbonisierung der Industrie mithilfe elektrischer Energie? In Proceedings of the 15th Symposium Energieinnovation, Graz, Austria, 14–16 February 2018; Technische Universität Graz, Ed.; Technische Universität Graz: Graz, Austria, 2018.
3. Wall, G. Exergy: A Useful Concept. Ph.D. Thesis, Chalmers Tekniska Högskola. N.S, Göteborg, Sweden, 1986.
4. Wall, G. Exergy tools. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2003**, *217*, 125–136. [CrossRef]
5. Dewulf, J.; van Langenhove, H.; Muys, B.; Bruers, S.; Bakshi, B.R.; Grubb, G.F.; Paulus, D.M.; Sciubba, E. Exergy: Its Potential and Limitations in Environmental Science and Technology. *Environ. Sci. Technol.* **2008**, *42*, 2221–2232. [CrossRef] [PubMed]
6. Statistik Austria. (Ed.) *Nutzenergieanalyse (NEA) 2017*; Statistik Austria: Wien, Austria, 2017.
7. Haas, R.; Panzer, C.; Resch, G.; Ragwitz, M.; Reece, G.; Held, A. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1003–1034. [CrossRef]
8. International Energy Agency. *Key World Energy Statistics*; Also Available on Smartphones and Tablets; International Energy Agency: Paris, France, 2017.
9. Kåberger, T. Progress of renewable electricity replacing fossil fuels. *Glob. Energy Interconnect.* **2018**, *1*, 48–52. [CrossRef]
10. Mancarella, P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy* **2014**, *65*, 1–17. [CrossRef]
11. Kriechbaum, L.; Scheiber, G.; Kienberger, T. Grid-based multi-energy systems—Modelling, assessment, open source modelling frameworks and challenges. *Energy Sustain. Soc.* **2018**, *8*, 244. [CrossRef]
12. Böckl, B.; Greiml, M.; Leitner, L.; Pichler, P.; Kriechbaum, L.; Kienberger, T. HyFlow—A Hybrid Load Flow-Modelling Framework to Evaluate the Effects of Energy Storage and Sector Coupling on the Electrical Load Flows. *Energies* **2019**, *12*, 956. [CrossRef]
13. Pfenninger, S.; Hawkes, A.; Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renew. Sustain. Energy Rev.* **2014**, *33*, 74–86. [CrossRef]
14. Szargut, J.; Morris, D.R. Cumulative exergy consumption and cumulative degree of perfection of chemical processes. *Int. J. Energy Res.* **1987**, *11*, 245–261. [CrossRef]
15. Rant, Z. Exergie—Ein neues Wort für die Technische Arbeitsfähigkeit. *Forsch. Auf Dem Geb. Ingenieurwesens 22* **1956**, *22*, 36–37.
16. Krause, T.; Kienzle, F.; Art, S.; Andersson, G. Maximizing exergy efficiency in multi-carrier energy systems. In Proceedings of the Energy Society General Meeting, Providence, RI, USA, 25–29 July 2010; pp. 1–8. [CrossRef]
17. Tsatsaronis, G. Definitions and nomenclature in exergy analysis and exergoeconomics. *Energy* **2007**, *32*, 249–253. [CrossRef]
18. Valero, A.; Lozano, M.A.; Munoz, M. A general theory of exergy saving: I. On the exergetic cost. In *Computer-Aided Engineering of Energy Systems: Vol 3. Second Law Analysis and Modelling, Proceedings of the Winter Annual Meeting of the American Society Mechan. Engin., Anaheim, California, 7–12 December 1986*; Gaggioli, R.A., Ed.; ASME: New York, NY, USA, 1986.
19. Lozano, M.A.; Valero, A. Theory of the exergetic cost. *Energy* **1993**, *18*, 939–960. [CrossRef]
20. Tsatsaronis, G. Thermoeconomic analysis and optimization of energy systems. *Prog. Energy Combust. Sci.* **1993**, *19*, 227–257. [CrossRef]
21. Sciubba, E. Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems. *Exergy Int. J.* **2001**, *1*, 68–84. [CrossRef]
22. Szargut, J. Towards a rational evaluation of steam prices. *Gospod. Cieptaa* **1957**, *5*, 104–106.
23. Sciubba, E. Exergy-based ecological indicators: From Thermo-Economics to cumulative exergy consumption to Thermo-Ecological Cost and Extended Exergy Accounting. *Energy* **2019**, *168*, 462–476. [CrossRef]
24. Ziębik, A.; Gładysz, P. Analysis of the cumulative exergy consumption of an integrated oxy-fuel combustion power plant. *Arch. Thermodyn.* **2013**, *34*, 105–122. [CrossRef]

25. Wang, S.; Liu, C.; Liu, L.; Xu, X.; Zhang, C. Ecological cumulative exergy consumption analysis of organic Rankine cycle for waste heat power generation. *J. Clean. Prod.* **2019**, *218*, 543–554. [CrossRef]
26. Valero, A.; Lozano, M.A.; Serra, L.; Torres, C. Application of the exergetic cost theory to the CGAM problem. *Energy* **1994**, *19*, 365–381. [CrossRef]
27. Valero, A.; Lozano, M.A.; Serra, L.; Tsatsaronis, G.; Pisa, J.; Frangopoulos, C.; von Spakovsky, M.R. CGAM problem: Definition and conventional solution. *Energy* **1994**, *19*, 279–286. [CrossRef]
28. Lozano, M.A.; Valero, A. Application of the exergetic costs theory to a steam boiler in a thermal generating station. In *Analysis and Design of Advanced Energy Systems: Applications, Proceedings of the Winter Meeting of the American Society of Mechanical Engineers, Boston, MA, USA, 13–18 December 1987*; Moran, M.J., Stecco, S.S., Reistad, G.M., Eds.; American Society of Mechanical Engineers. Winter Annual Meeting. American Society of Mechanical Engineers. Advanced Energy Systems Division. AES (Series); ASME: New York, NY, USA, 1987.
29. Misra, R.D.; Sahoo, P.K.; Gupta, A. Application of the exergetic cost theory to the LiBr/H_2O vapour absorption system. *Energy* **2002**, *27*, 1009–1025. [CrossRef]
30. Ertesvåg, I.S. Society exergy analysis: A comparison of different societies. *Energy* **2001**, *26*, 253–270. [CrossRef]
31. Ukidwe, N.U.; Bakshi, B.R. Industrial and ecological cumulative exergy consumption of the United States via the 1997 input–output benchmark model. *Energy* **2007**, *32*, 1560–1592. [CrossRef]
32. Sun, B.; Nie, Z.; Gao, F. Cumulative exergy consumption (CExC) analysis of energy carriers in China. *Int. J. Exergy* **2014**, *15*, 196. [CrossRef]
33. Causone, F.; Sangalli, A.; Pagliano, L.; Carlucci, S. An Exergy Analysis for Milano Smart City. *Energy Procedia* **2017**, *111*, 867–876. [CrossRef]
34. Torío, H.; Schmidt, D. Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis. *Energy Build.* **2010**, *42*, 1601–1609. [CrossRef]
35. Li, H.; Svendsen, S. Energy and exergy analysis of low temperature district heating network. *Energy* **2012**, *45*, 237–246. [CrossRef]
36. Bösch, M.E.; Hellweg, S.; Huijbregts, M.A.J.; Frischknecht, R. Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. *Int. J. Life Cycle Assess.* **2007**, *12*, 181–190. [CrossRef]
37. Hilpert, S.; Kaldemeyer, C.; Krien, U.; Günther, S.; Wingenbach, C.; Plessmann, G. The Open Energy Modelling Framework (oemof)—A new approach to facilitate open science in energy system modelling. *Energy Strategy Rev.* **2018**, *22*, 16–25. [CrossRef]
38. Oemof Developer Group. *Oemof—Open Energy Modelling Framework (v0.2.2)*; Oemof Developer Group: Berlin, Germany, 2018; doi:10.5281/zenodo.1302372. [CrossRef]
39. United Nations. (Ed.) *International Recommendations for Energy Statistics (IRES)*; Statistical Paper Series M; United Nations: New York, NY, USA, 2017.
40. Böckl, B.; Kriechbaum, L.; Kienberger, T. Analysemethode für kommunale Energiesysteme unter Anwendung des zellularen Ansatzes. In *Symposium Energieinnovation*; Institut für Elektrizitätswirtschaft und Energieinnovation, Ed.; TU Graz: Graz, Austria, 2016.
41. Kleinertz, B.; Pellinger, C.; von Roon, S.; Hübner, T.; Kaestle, G. *EU Displacement Mix: A Simplified Marginal Method to Determine Environmental Factors for Technologies Coupling Heat and Power in the European Union*; Forschungstelle für Energiewirtschaft eV: Munich, Germany, 2018.
42. Frischknecht, R.; Stucki, M.; Flury, K.; Itten, R.; Tuchschmid, M. *Primärenergiefaktoren von Energiesystemen: Version 2.2*; ESU-Services Ltd.: Uster, Switzerland, 2012.
43. oemof Developer Group. *The Oemof Demandlib (Oemof. Demandlib)*; oemof Developer Group: Berlin, Germany, 2016; doi:10.5281/ZENODO.438786. [CrossRef]
44. Pfenninger, S.; Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **2016**, *114*, 1251–1265. [CrossRef]
45. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239. [CrossRef]
46. Hellwig, M. Entwicklung und Anwendung parametrisierter Standard-Lastprofile. Ph.D. Thesis, Technische Universität München, München, Germany, 2003.
47. BDEW/VKU/GEODE. *BDEW/VKU/GEODE—Leitfaden: Abwicklung von Standardlastprofilen Gas*; BDEW/VKU/GEODE: Berlin, Germany, 2015.

48. E-Control. *Sonstige Marktregeln Strom*; Kapitel 6—Zählwerte, Datenformate und standardisierte Lastprofile; E-Control: Wien, Austria, 2012.
49. Probas. Holz-EU-KUP-Pellet-Heizung-50 kW-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7B4D4E8B6D-1FEC-45E5-B927-7977C6455186%7D (accessed on 17 October 2019).
50. Probas. Gas-Heizung-Brennwert-DE-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7BE949C50B-659D-42C4-A779-2FCCD9CCA9AF%7D (accessed on 17 October 2019).
51. Probas. el.heat pump-mono-CZ. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7BCC0E4B28-80DA-11D4-9E81-0080C8426C9A%7D (accessed on 17 October 2019).
52. Ausfelder, F.; Dura, H.E. (Eds.) *Optionen für ein nachhaltiges Energiesystem mit Power-to-X Technologien: Herausforderungen—Potenziale—Methoden—Auswirkungen: 1. Roadmap des Kopernikus-Projektes "Power-to-X": Flexible Nutzung erneuerbarer Ressourcen (P2X): Erstellt im Rahmen der Roadmapping-Aktivitäten im Koperinkus-Projekt "Power-to-X": Flexible Nutzung erneuerbarer Ressourcen (P2X) gefördert durch das Bundesministerium für Bildung und Technologie*, 1st ed.; DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V: Frankfurt am Main, Germany, 31 August 2018.
53. Probas. el.heating-CZ. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7BCC0E4B29-80DA-11D4-9E81-0080C8426C9A%7D (accessed on 17 October 2019).
54. Probas. Holz-HS-Waldholz-HKW-DM-DE-2005/brutto. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7B67221E5B-47FF-45D8-B8E2-08DF837417C3%7D (accessed on 17 October 2019).
55. Probas. Gas-BHKW-250-DE-2010/en. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7B4C6CB40B-4922-4648-9922-31CE39A826C0%7D (accessed on 17 October 2019).
56. Peters, J.F.; Baumann, M.; Zimmermann, B.; Braun, J.; Weil, M. The environmental impact of Li-Ion batteries and the role of key parameters—A review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 491–506. [CrossRef]
57. heizungsdiscount24.de. 10000 Liter TWL Puffer, Pufferspeicher Typ P10000. Available online: https://www.heizungsdiscount24.de/speichertechnik/10000-liter-twl-puffer-pufferspeicher-typ-p10000.html (accessed on 17 October 2019).
58. Deutz, S.; Bongartz, D.; Heuser, B.; Kätelhön, A.; Schulze Langenhorst, L.; Omari, A.; Walters, M.; Klankermayer, J.; Leitner, W.; Mitsos, A.; et al. Cleaner production of cleaner fuels: Wind-to-wheel—environmental assessment of CO_2—based oxymethylene ether as a drop-in fuel. *Energy Environ. Sci.* **2018**, *11*, 331–343. [CrossRef]
59. Probas. Solar-PV-multi-Rahmen-mit-Rack-DE-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7B05EC9CDC-9418-45CD-A333-A1CC3CCF7C48%7D (accessed on 17 October 2019).
60. Probas. Wind Mill-CZ. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7BCC0E4E86-80DA-11D4-9E81-0080C8426C9A%7D (accessed on 17 October 2019).
61. Fratzscher, W.; Brodjanskij, V.; Michalek, K. *Exergie: Theorie und Anwendung*; Springer: Berlin/Heidelberg, Germany, 2013.
62. Probas. MetallStahl-mix-DE-2010. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={F428D8DE-27A7-4FD6-850C-4C0DC39740DE} (accessed on 17 October 2019).
63. Probas. Chem-OrgPVC-mix-DE-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={C0A5A645-F236-4D6F-8B75-24DB0D899824} (accessed on 17 October 2019).
64. Probas. Steine-ErdenZement-DE-2010. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={8BBACD2C-DA5F-43A7-B24B-0D49BA161D26} (accessed on 17 October 2019).
65. Probas. Chem-OrgHDPE-DE-2000. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={0E0B299A-9043-11D3-B2C8-0080C8941B49} (accessed on 17 October 2019).
66. Probas. MetallAluminium-mix-DE-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={5CAE9D2B-4C86-4244-88B2-A79E09DC870B} (accessed on 17 October 2019).

67. Probas. MetallKupfer-DE-mix-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={AB07F312-569F-452A-82B5-3BF124101151} (accessed on 17 October 2019).
68. Probas. FabrikSilizium-Modul-multi-DE-2030. Available online: https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={C8A517A8-CC5B-4559-9747-E385A6E4FC39} (accessed on 17 October 2019).

12 PAPER 3

Modelling Grid Constraints in a Multi-Energy Municipal Energy System using Cumulative Exergy Consumption Minimisation

energies

Article

Modelling Grid Constraints in a Multi-Energy Municipal Energy System Using Cumulative Exergy Consumption Minimisation

Lukas Kriechbaum *, Philipp Gradl, Romeo Reichenhauser and Thomas Kienberger

Energy Network Technology, Montanuniversitaet Leoben, Franz-Josef-Straße 18, A-8700 Leoben, Austria; philipp.gradl@unileoben.ac.at (P.G.); romeo-manuel.reichenhauser@stud.unileoben.ac.at (R.R.); thomas.kienberberger@unileoben.ac.at (T.K.)

* Correspondence: lukas.kriechbaum@unileoben.ac.at; Tel.: +43-3842-402-5408

Received: 7 June 2020; Accepted: 29 July 2020; Published: 30 July 2020

Abstract: Efficiency measures and the integration of renewable energy sources are key to achieving a sustainable society. The cumulative exergy consumption describes the resource consumption of a product from the raw material to the final utilisation. It includes the exergy expenses for energy infrastructure as well as the imported energy. Since consumers and renewable potentials are usually in different locations, grid restrictions and energy flows have a significant impact on the optimal energy system design. In this paper we will use cumulative exergy minimisation together with load flow calculations to determine the optimal system design of a multi-cell municipal energy system. Two different load flow representations are compared. The network flow model uses transmission efficiencies for heat, gas and electricity flows. The power flow representation uses a linear DC approximated load flow for electricity flows and a MILP (mixed integer linear programming) representation for heat and gas flows to account for the nonlinear pressure loss relation. Although both representations provide comparable overall results, the installed capacities in the individual cells differ significantly. The differences are greatest in well meshed cells, while they are small in stub lines.

Keywords: energy systems optimisation; exergy analysis; multi-energy systems; energy-system design; municipal energy systems; cumulative-exergy consumption minimisation; optimal power flow

1. Introduction

The European Union's (EU) climate neutrality goals [1] require a shift in the energy system from fossil fuels towards renewable energy sources (RES). Statistics [2] show a 14% share of RES in gross available energy in the EU-28 (ranging from 5% in the Netherlands and Malta to 43% in Latvia). In some countries, today's local energy demand exceeds the available RES potentials, for example in Austria [3,4]. In such cases, efficiency measures and/or RES imports from other countries are key to reach the goal of a sustainable society.

Exergy is a useful concept to identify efficiency potentials. Exergy is defined as the maximum useful work that can be extracted from any form of energy. It is the driving potential contained in energy that causes a thermodynamic change of state. Unlike energy, which is subject to the law of conservation, exergy is always consumed when brought to equilibrium with its surroundings. Without an external supply, changes of state can only occur from higher to lower exergy levels. Therefore, as exergy flows through the energy system, it constantly deteriorates until its final use [5].

While mechanical work, electricity and chemical energy carriers can be considered as pure exergy, the exergy content of heat is dependent on the temperature difference between the heat θ and the ambient state θ_{amb}. This is equivalent to the Carnot efficiency η_C. The lower the temperature difference, the lower the exergy content.

$$\eta_C = \frac{\theta - \theta_{amb}}{\theta} \quad (1)$$

Electricity accounts for only 22% of final energy consumption in the Organisation for Economic Co-operation and Development (OECD) countries [6]. Heat usually takes a much larger share; for example, in Austria it is 50.7% [7]. Nevertheless, their energy strategies tend to focus on decarbonising the electricity sector [8]. With an integrated approach, in which several sectors (households, industry, transport, etc.) and energy carriers (electricity, heat, natural gas, hydrogen, biomass, etc.) are considered in a so-called multi-energy system (MES), synergies can be used for further decarbonisation [8,9]. Appropriate coupling technology (e.g., heat pumps, combined heat and power plants (CHP), etc.) and storages (e.g., batteries, pumped hydro, thermal energy storage, etc) are necessary to provide the flexibility for the integration of variable RES [9]. In addition, the necessary energy networks must be taken into account, since renewable potentials and consumers are usually located in different places [10]. In such cases, MES can also reduce the strain on energy transmission and distribution infrastructure [11].

2. State of Research and Research Objective

Exergy is a good common basis in MES when comparing different forms of energy [12]. The main objective of all methods and tools of exergy analysis presented in the literature is to enhance resource efficiency [13,14]. Examples comprise of thermo-economics [15], cumulative exergy consumption [16], exergetic cost theory [17,18] and extended exergy analysis [19]. The main differences between the individual methods are in the selected system boundaries. In this work we focus on the cumulative exergy consumption (CExC) methodology, which we extend by load flow calculations.

2.1. Cumulative Exergy Consumption

The CExC concept, introduced by Szargut et al. [16], describes the resource consumption to provide a product or service. It quantifies the exergy consumption from the raw materials or energy carriers to their final utilisation in a product or a service [20]. Therefore, by using a fuel-product concept, it describes the exergy expenditures to produce a single product unit. The same results can be obtained by the exergetic cost theory developed by Valero et al. [17], even though it uses a different formalisation [14].

On a technical level the CExC methodology was applied to chemical processes [16], oxy-fuel combustion plants [21], organic Rankine cycle pants for waste heat utilisation [22]. On a larger scale, it was used to analyse the resource efficiency of whole countries and societies [23], including China [24] and the United States [25]. In Milan, CExC was used to compare different energy scenarios in smart city planning processes [26]. Kriechbaum and Kienberger proposed the CExC-minimisation to obtain the optimal design of municipal energy systems with high shares of RES [27].

2.2. Multi-Energy-Systems

A Multi-Energy-System (MES) is a holistic consideration of an energy system, covering the "stages from the extraction and treatment (e.g., gas well, coal mine, sun) to the services (e.g., heating, illumination, transport), while also considering the different carriers (e.g., electricity, natural gas, oil, coal)" [9]. According to Mancarella [28], MES can be characterised by four categories: multi-service, multi-fuel, spatial and network. Multi-fuel means that an energy service can be supplied by multiple fuels (e.g., domestic heat production by a resistance heater or a heat pump). Multi-service means that one fuel type can supply multiple energy services (e.g., electricity and heat from a CHP-plant). The spatial category outlines the different levels of aggregation (e.g., buildings, districts, provinces, etc.), while the network category discusses the influence of electricity, heat and gas grids. The cellular approach [29] is a flexible aggregation concept. RES, conversion units, storage and demand are merged into cells according to geographical criteria; the size of the individual cells depends on the task. Those cells are then connected by the different energy grids.

The energy hub concept is the most generic MES modelling approach [30]. It was developed to analyse the power flows of different energy carriers in grid-based MES [31]. Since then this concept has been widely used in literature [32], for example for OPF (optimal power flow) applications [31], topological optimisation [33] and reliability considerations [34]. The microgrid [35] and the virtual power plant [36] modelling concepts also consider some MES aspects, even though they were primarily developed for electricity grid modelling. A microgrid modelling approach was used to minimise daily operational costs in their ploy-generation microgrid at the Savon Campus of Genoa University [37]. In a feasibility study, a virtual power plant approach is used to assess the feasibility of power balancing in an electricity grid consisting solely of renewable energies with CHP-plants, heat pumps and thermal storage [38].

2.3. Load Flow Calculations

The main objective of load flow calculations in electric grids is the determination of complex nodal voltages and its dependent quantities such as line flows, currents and losses [39]. For alternating current (AC) networks, such load flow calculations result in a set of nonlinear equations. In optimal power flow (OPF) such power flow equations are used to determine the optimal operation of electrical grids while at the same time considering the electrical laws and engineering limits [40]. Such a general OPF problem results in a mixed-integer-nonlinear, non-convex and largescale optimisation problem [41]. Many developed OPF solution methods have distinct mathematical and computational requirements, but to date, no general formulation and solution approach is available for all various forms of OPF [42].

The OPF modelling detail depends on the goal and purpose of the application. Long term planning models use coarser temporal and spatial data aggregation compared to short term operational models [40]. Since this paper deals with system design and planning, we will further focus on the coarser models. Geidl [43] proposed a classification in network flow and power flow models. Network flow models show little modelling detail and can be further divided in type I (no losses) and type II (losses modelled as transmission efficiency). Power flow models are based on physical principles linking voltage and current or pressure and mass flow. For electricity they can be further divided into full AC and simplified linear approximated DC models [44]. Linear, piecewise-linear and nonlinear models for heat and gas flows are available.

While there are thousands of published papers focusing solely on the electric power system OPF [40], the optimal power flow of multiple energy carriers (electricity, heat and gas) has not received much attention yet. Most work published in this field is related to the "Energy Hub" concept [45]. Geidl and Andersson [31] compared the non-linear power flow of electricity, heat and gas networks to the standard dispatch methods for electrical power systems. Shao et al. [46] presented a MILP-OPF formulation of electricity and natural gas flows. Integrated optimal power flow for urban electricity, heat and gas networks is investigated by Xu et al. [47]. Krause et al. [12] investigated exergy efficient operation of a MES using OPF. The integrated electricity and natural gas power flow of an electric IEEE-14 test grid connected to the Belgian gas grid was investigated by Unsihuay et al. [48] using an evolutionary optimisation together with the Newton and interior point methods.

2.4. Research Objective and Paper Outline

Exergy-efficient energy systems are essential, especially since the RES potentials are usually limited. The time-varying nature of electricity production from PV (photovoltaic) and wind calls for models that combine planning and operational aspects [49]. Therefore, when designing exergy optimal energy systems, generally the following two research questions need to be answered:

- System design: How can the optimum capacity of storages and conversion units be determined?
- System operation: How can such a system be operated while always meeting the demand?

A basic methodology to answer both was developed by the authors in [27]. CExC-minimisation was used together with single cell model to calculate the optimal installed capacities of RES, storages and conversion units. However, geographical factors such as spatial dimension, the local availability of RES and the transport capacities of the energy networks were neglected. In this paper we will particularly focus on these points. Therefore, the aim is to answer the following research questions:

- What is the impact of maximum grid capacities on installed RES, storage and conversion unit capacities and their operation?
- What is the impact of different load flow representations (network flow vs. power flow)?
- What influence do the spatially unevenly distributed RE potentials have? High potentials typically exist in thinly populated rural regions, low potentials in densely populated cities.

To answer these questions we combine the CExC methodology [16] with load flow calculations. This and the corresponding problem formulation are presented in Section 2. A case study using a multi-cell model and different load flow representations is carried out. Together with its results, this is presented in Section 3. The paper concludes with a discussion of the results in Section 4.

3. Methodology

In this work we use CExC-minimisation together with network and power flow calculations to determine the optimal design of a multi-cell municipal MES. We use a brownfield modelling approach. This means that existing infrastructure will be considered in the model. In our case, we assume that the energy networks are given and want to determine the installed capacities of RES, conversion units and storages. This requires modelling the individual components of the energy system, including the energy grids connecting the individual cells. The optimum system design is reached when the energy system's CExC reaches a minimum. For load flow modelling we will compare a linear network flow formulation to a MILP power flow formulation. The MILP formulation is used to piecewise linearise the nonlinear pressure loss in heat and gas pipes.

3.1. Formulation of the Optimisation Problem

Such a CExC-minimisation task can be formulated as a general constrained optimisation problem [50], of which the most general form is:

$$f = \min F(x, y) \tag{2}$$

$$h(x, y) = 0 \tag{3}$$

$$g(x, y) \leq 0 \tag{4}$$

Equation (2) is the objective function, which only consists of linear variables and delivers a scalar value. Equations (3) and (4) generally describe the equality and inequality constraints, respectively, where x are the continuous and y are the integer variables. In this work integer variables are only needed for the power flow calculations.

3.2. Cumulative Exergy Consumption Minimisation

CExC-minimisation is an option to obtain an exergy optimal energy system. This means that the difference between total CExC expenditures B_t^{*X} and total exergy yields B_t^Y must become a minimum. The objective function can therefore be formulated as follows:

$$\min F(x, y) = B_t^{*X} - B_t^Y \tag{5}$$

where total expenditures B_t^{*X} are the sum of the expenditures for the individual components $x_1, x_2, \ldots \in X = \{\textit{electricity import, battery, CHP, PV, } \ldots \}$. They can be categorised into four groups (Figure 1):

storages $s_1, s_2, \ldots \in S$ = *{battery, H_2 tank,...}*, conversion units $c_1, c_2, \ldots \in C$ = *{gas boiler, CHP,...}*, RES $r_1, r_2, \ldots \in R$ = *{PV, wind,...}* and imports $i_1, i_2, \ldots \in I$ = *{electricity, natural gas,...}*. Total CExC expenditures can be calculated for each group (Equation (6)).

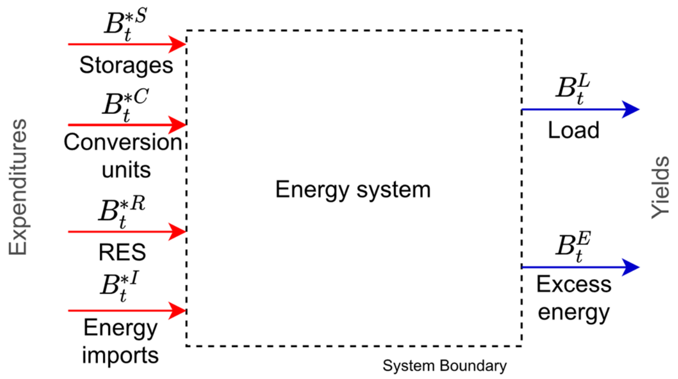

Figure 1. Cumulative exergy consumption (CExC)-expenditures (imports, renewable energy sources (RES), storages and conversion units) and yields (load and excess).

Total yields B_t^Y are the sum of the yields of the individual components $y_1, y_2, \ldots \in Y$ = *{excess electricity, heat load, … }*. They can be further categorised into two groups (Figure 1): loads $l_1, l_2, \ldots \in L$ = *{electricity load, heat load, … }* and excess energy $e_1, e_2, \ldots \in E$ = *{excess electricity, excess heat, … }*. Equation (7) is used to calculate groupwise and total exergy yields. For expenditures, all previous exergy consumption is cumulated; for revenue, the actual physical exergy contents are used. A detailed description of the assessment of expenditures and yields can be found in Kriechbaum and Kienberger [27].

$$B_t^{*X} = \sum_{x \in X} B_x^{*X} = \sum_{s \in S} B_s^{*S} + \sum_{c \in C} B_c^{*C} + \sum_{r \in R} B_r^{*R} + \sum_{i \in I} B_i^{*I} \quad (6)$$

$$B_t^{Y} = \sum_{y \in Y} B_y^{Y} = \sum_{l \in L} B_l^{L} + \sum_{e \in E} B_e^{E} \quad (7)$$

Energy transmission components $t_1, t_2, \ldots \in T$ = *{electric line, heat pipeline, gas pipeline, … }* are not listed here, as they are considered as existing infrastructure. Therefore, they do not cause additional CExC expenditures. However, constraints are created to model the behaviour of the different grids. All components in the model are connected via buses $b_1, b_2, \ldots \in B$ = *{electric bus, heat bus, gas bus, … }*. No expenses are incurred for these buses.

3.3. Energy System Components

An energy system consists of different individual components. Sources and sinks are used to model energy flows over the system boundaries (Figure 2). The internal structure consists of conversion units, storages and transmission lines. They are used to convert the energy carriers to the desired forms of energy and deliver it to the consumers to meet their load.

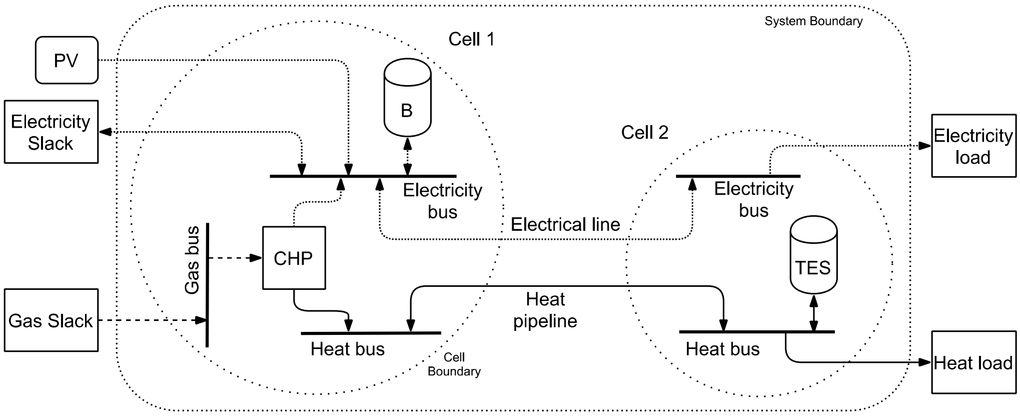

Figure 2. Example of a multi-cell open energy modelling framework (oemof) energy system model with slacks nodes, loads, RES, conversion units, storages, electrical lines and heat pipelines and busses.

For each component in the energy system, the equality and inequality constraints as well as the corresponding parts of the objective function must be added to the optimisation model. The constraints include maximum values, fixed time series for loads and RES, conversion efficiencies as well as the load flow equations. The objective function is composed of the expenditures and yields of the individual components. The expenditures B_x^{*X} comprise an investment and operating share. For an expenditure component x they are calculated according to Equation (8):

$$B_x^{*X} = P_{x,inst}^X \cdot r_x^{*p,X} + \sum_t (P_x^X(t) \cdot r_x^{*X} \cdot \tau) \tag{8}$$

The first term describes investment expenditures, where $P_{x,\, inst}^X$ is the installed capacity and $r_x^{*p,X}$ is the equivalent periodic CExC-factor [27]. The equivalent periodic CExC-factor describes the CExC per unit of installed capacity for a given period (in our case one year). The second term relates to the operational expenditures. P_x^X refers to the actual power produced in timestep t, τ is the time increment and r_x^{*X} is the CExC-factor [27]. The CExC-factor describes the CExC per unit of consumed energy. Not all components have both an investment and an operating part.

Yields only have an operational part and they are assessed by their exergy content r_y^Y. Therefore, the exergy B_y^Y of a general yield component y is calculated:

$$B_y^Y = \sum_t \left(P_y^Y(t) \cdot r_y^Y \cdot \tau\right) \tag{9}$$

In this work we use oemof (open energy modelling framework) [51,52] for model generation. It provides ready-to-use models for the basic energy system components (sources, sinks, conversion units, storages, busses, basic energy transmission models). For this work we extend it with power flow models for heat and gas flows and the respective busses. Individual components can only be connected via a bus, busses can be either connected by conversion units or energy networks (Figure 2). Several busses and their adjacent components can be grouped to cells [29].

3.3.1. Energy Imports, Loads and Excess Energy

Imports, loads and excess energy are flows of energy carriers over the system boundary, for example electricity or gas exchange with their respective slacks (Figure 2). To model those, the oemof components source and sink are used. Imports are flows of pre-processed energy carriers such as electricity, natural gas, biomass or industrial waste heat into the energy system. They have a maximum power $P^{I}_{i,max}$ constraint (Equation (10)) and the CExC B^{*I}_{i} is added to the objective function (Equation (11)). No investment expenditures are incurred, as they are already included in the CExC-factor r^{*I}_{i}.

$$P^{I}_{i}(t) - P^{I}_{i,max}(t) \leq 0 \tag{10}$$

$$B^{*I}_{i} = \sum_{t} P^{I}_{i}(t) \cdot r^{*I}_{i} \cdot \tau \tag{11}$$

Loads are flows of energy carriers to the consumers, for example electricity, process heat or domestic heat. The demand time-series are given, and therefore, the actual values $P^{L}_{l,actv}$ of any load is prescribed (Equation (12)). The yield B^{L}_{l} is the exergy delivered to the consumer (Equation (13)):

$$P^{L}_{l}(t) - P^{L}_{l,actv}(t) = 0 \tag{12}$$

$$B^{L}_{l} = \sum_{t} P^{L}_{l}(t) \cdot r \cdot \tau \tag{13}$$

Excess energy P^{E}_{e} are energy carriers that are neither consumed nor stored locally and are returned to the grid. In our case this only applies to electricity. Excess energy has a maximum power $P^{E}_{e,max}$ constraint (Equation (14)). The yield is the exergy B^{E}_{e} stored in the energy carrier (Equation (15)).

$$P^{E}_{e}(t) - P^{E}_{e,max}(t) \leq 0 \tag{14}$$

$$B^{E}_{e} = \sum_{t} P^{E}_{e}(t) \cdot r^{E}_{e} \cdot \tau \tag{15}$$

3.3.2. RES

RES includes electricity produced by wind and PV. Their time-series are given, and therefore, an actual value $P^{R}_{r,actv}$ is prescribed (Equation (16)). Since RES potentials are usually limited, a maximum capacity $P^{R}_{r,inst,\ max}$ constraint is added (Equation (17)). RES CExC B^{*R}_{r} comprise both investment and operating expenditures (Equation (18)). In the case of RES, the CExC-factor is equal to the exergy-factor r^{R}_{r} [53].

$$P^{R}_{r}(t) - P^{R}_{r,actv}(t) = 0 \tag{16}$$

$$P^{R}_{r,inst} - P^{R}_{r,inst,\ max} \ \leq\ 0 \tag{17}$$

$$B^{*R}_{r} = P^{R}_{r,inst} \cdot r^{*p,R}_{r} + \sum_{t} P^{R}_{r}(t) \cdot r^{R}_{r} \cdot \tau \tag{18}$$

3.3.3. Conversion Units

Conversion units such as boilers, CHPs or heat pumps can have single or multiple inputs $P_{c,in}$ and outputs $P_{c,out}$. For a set of different energy carriers α, β, … ∈ Γ = {electricity, natural gas, heat, hydrogen, biomass, … }, energy conversion is modelled using a conversion matrix C_c, which consists of the conversion efficiencies η_c [33]. Therefore, the following constraints are added:

$$\underbrace{\begin{pmatrix} P^{\alpha}_{c,out}(t) \\ P^{\beta}_{c,out}(t) \\ \vdots \\ P^{\omega}_{c,out}(t) \end{pmatrix}}_{P_{c,out}} = \underbrace{\begin{pmatrix} \eta^{\alpha,\alpha}_{c} & \eta^{\beta,\alpha}_{c} & \cdots & \eta^{\omega,\alpha}_{c} \\ \eta^{\alpha,\beta}_{c} & \eta^{\beta,\beta}_{c} & \cdots & \eta^{\omega,\beta}_{c} \\ \vdots & \vdots & \ddots & \vdots \\ \eta^{\alpha,\omega}_{c} & \eta^{\beta,\omega}_{c} & \cdots & \eta^{\omega,\omega}_{c} \end{pmatrix}}_{C_c} * \underbrace{\begin{pmatrix} P^{\alpha}_{c,in}(t) \\ P^{\beta}_{c,in}(t) \\ \vdots \\ P^{\omega}_{c,in}(t) \end{pmatrix}}_{P_{c,in}} \tag{19}$$

As there are several interdependent inputs and outputs, one of them must be defined as a reference $P^C_{c,ref}$. The installed capacity $P^C_{c,inst}$ and the equivalent periodic CExC-factor $r_c^{*p,C}$ refer to this reference. The reference input or output must be always less than or equal to the installed capacity (Equation (20)). The expenditures are the CExC B^{*C} necessary to install a conversion unit (Equation (21)):

$$P^C_{c,ref}(t) - P^C_{c,inst} \leq 0 \tag{20}$$

$$B_c^{*C} = P^C_{c,inst} \cdot r_c^{*p,C} \tag{21}$$

3.3.4. Storages

A differential energy balance between two consecutive timesteps is used to model energy storage. The change in state of energy SOE_s describes the currently stored energy, where $\eta_{s,in}$ and $\eta_{s,out}$ are the input and output efficiencies and $\eta_{s,loss}$ are the standby losses:

$$\Delta SOE_s(t) = [\eta_{s,in} \cdot P_{s,in}(t) - \eta_{s,out} \cdot P_{s,out}(t)] \cdot \tau - \eta_{s,loss} \cdot SOE_s(t-1) \tag{22}$$

The current SOE_s of energy must always be less than or equal to the installed capacity $C^S_{s,inst}$ (Equation (23)). The expenditures are the CExC B_s^{*S} necessary to install a conversion unit (Equation (24)):

$$SOE_s(t) - C^S_{s,inst} \leq 0 \tag{23}$$

$$B_s^{*S} = C^S_{s,\ inst} \cdot r_s^{*p,S} \tag{24}$$

3.3.5. Energy Transmission

For energy transmission, two different models are compared. Basic and simplified network flow models are compared with higher detail power flow models. The network flow models only consider energy losses and are equivalent for all energy carriers. The power flow models also consider the driving potential such as voltage or pressure in electricity, heat and natural gas grids, respectively.

Network flow models only use two constraints. One describes the transmission losses using the transmission efficiency η_t^T (Equation (25)). The other one limits the maximum capacity $P^T_{t,max}$ (Equation (26)):

$$P^T_{t,in}(t) \cdot \eta_t^T - P^T_{t,out}(t) = 0 \tag{25}$$

$$P^T_{t,in}(t) - P^T_{t,max} \leq 0 \tag{26}$$

The power flow models require additional constraints representing the physical power flow relations. For the electricity flows we assume that the ohmic resistance R is negligibly small compared to the reactance X_t^T. In such a case, we can use a DC-approximated power flow model [11], where the transmitted power $P_t^{T,el}$ is only dependent on the voltage angles $\Theta^{T,el}_{t,in}$ and $\Theta^{T,el}_{t,out}$, and the reactance $X_t^{T,el}$:

$$P_t^{T,el}(t) = \frac{\Theta^{T,el}_{t,in} - \Theta^{T,el}_{t,out}}{X_t^{T,el}} \tag{27}$$

For heat and natural gas flows the non-linear relationship between power $P_t^{T,g,h}$ and pressure drop ($p^{T,g,h}_{t,in}$, $p^{T,g,h}_{t,out}$) is represented by piecewise linearised functions. The resistance $R_t^{T,g,h}$ depends on the properties of the pipe Φ_t^P (diameter, length, roughness, etc.) and the fluid Φ_t^F (pressure, temperature, composition). A detailed derivation is shown in the Appendix A.

$$P_t^{T,g,h}(t) = \frac{\sqrt{p_{t,in}^{T,g,h} - p_{t,out}^{T,g,h}}}{R_t^{T,g,h}\left(\Phi_t^P, \Phi_t^F\right)} \tag{28}$$

3.3.6. Busses

All components such as conversion units, storages or transmission lines are connected via busses in which all power flows ($P_{b,in}^B$, $P_{b,out}^B$) are balanced. Therefore, we add the following constraint for any bus:

$$\sum_{in} P_{b,in}^B(t) - \sum_{out} P_{b,out}^B(t) = 0 \tag{29}$$

For the power flow models, additional constraints are necessary. They balance and limit voltage angles and pressure levels. At any electrical bus just one voltage angle $\Theta_b^{B,el}$ is allowed, which is equal to the voltage angles of all inflows $\Theta_{b,in}^{B,el}$ and outflows $\Theta_{b,out}^{B,el}$ (Equation (30)). The voltage angles must stay within their bounds of $\Theta_{b,min}^{B.el}$ and $\Theta_{b,max}^{B,el}$ (Equation (31)):

$$\Theta_b^{B,el}(t) = \Theta_{b,in}^{B,el}(t) = \Theta_{b,out}^{B,el}(t) \tag{30}$$

$$\Theta_{b,min}^{B.el} \leq \Theta_b^{B,el}(t) \leq \Theta_{b,max}^{B,el} \tag{31}$$

For heat and natural gas networks the same rules apply for the pressure level $p_b^{B,g,h}$ in the busses:

$$p_b^{B,g,h}(t) = p_{b,in}^{B,g,h}(t) = p_{b,out}^{B,g,h}(t) \tag{32}$$

$$p_{b,min}^{B,g,h} \leq p_b^{B,g,h}(t) \leq p_{b,max}^{B,g,h} \tag{33}$$

4. Case Study

We have designed a case study that aims to answer our research questions. It combines CExC-minimisation, a multi-cell energy system and network and power flow representations. For a given demand, grid capacities and renewable potentials, the optimal operation and installed capacities of energy conversion units and storage facilities shall be determined. The different results of the network flow(NF) model and the power flow (PF) model will be discussed.

4.1. System Description

We use a simplified model city, which is divided into four cells. Simplification is carried out according to the cellular approach [29]. The cells represent the areas typical for a city: city centre (CC), suburbs (CS), industrial areas (CI) and rural areas (CR) (Figure 3). In any cell, a range of conversion technology, storages and RES for possible installation is provided. We use the same components as used in [27]: battery, thermal energy storage (TES), H_2-Storage, PV, wind, biomass boiler, gas boiler, heat pump, PEM electrolyser, PEM fuel cell, resistance heater, biomass CHP, gas CHP. All relevant data such as efficiencies and equivalent periodic CExC factors are overtaken from there. Tables presenting this data are provided in the Appendix B.

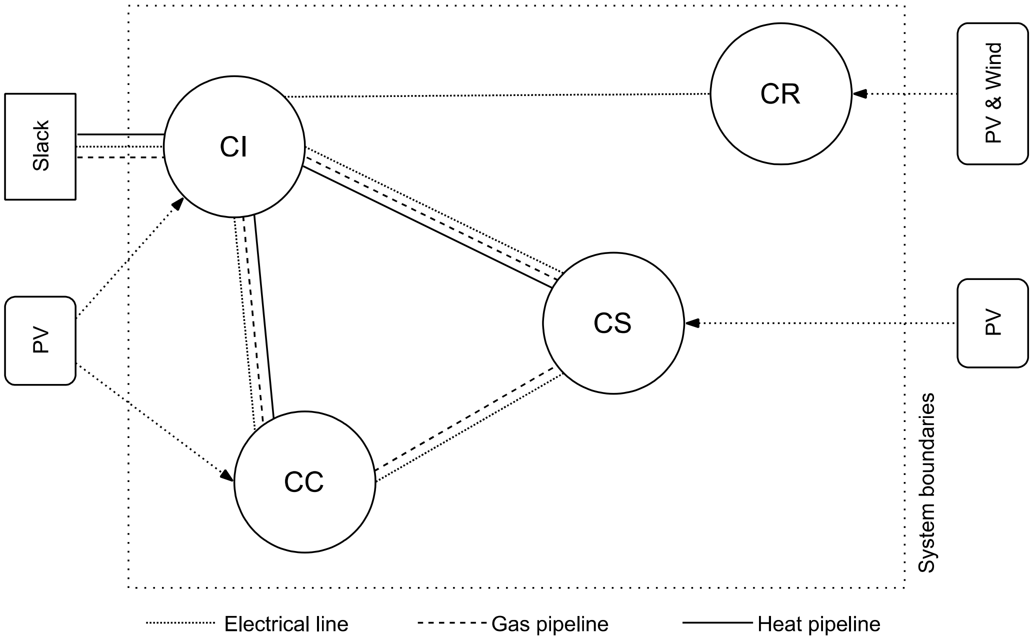

Figure 3. Network topology of the model city and available RES potentials. CC: city centre, CS: suburbs, CI: industrial areas and CR: rural areas.

Each imported energy carrier (electricity and natural gas from the transmission grids, waste heat from an industrial plant, biomass from the rural areas) needs to be assessed by its CExC-factor (Table 1). Again, we apply the values of [27], which correspond to the current CExC-factors. An exception is made for electricity. The current CExC-factor is 2.96, but we use a lower value of 2 because this already corresponds to a future energy system with a higher share of renewable energy sources.

Table 1. CExC-factors for the different imported energy carriers [27].

	Electricity	**Natural Gas**	**Waste Heat**	**Biomass**
CExC-factor r_i^I in $\frac{MWh}{MWh}$	2.0	1.21	0.21	1.1

The connection to the slack nodes for energy import is in CI. While the connection for electricity is bidirectional, gas and waste heat can only be obtained from the source. The cells are connected by electricity, natural gas and heat grids. While all cells are covered by the electricity grid, only the denser populated cells are connected to the natural gas and heat grids. Maximum transmission capacities and efficiencies can be found in Table 2.

Table 2. Installed slack node capacities and installed grid capacities and efficiencies.

		Electricity	**Natural Gas**	**Heat**
CI-Slack	Max. cap. $P^I_{CI-S,max}$	600 MW	1000 MW	20 MW
CI-CC	Max. cap. $P^T_{CI-CC,max}$ Efficiency η^T_{CI-CC}	36 MW 99.9%	163 MW 99.9%	30 MW 85%
CI-CS	Max. cap. $P^T_{CI-CS,max}$ Efficiency η^T_{CI-CS}	36 MW 99.9%	141 MW 99.9%	30 MW 85%
CC-CS	Max. cap. $P^T_{CC-CS,max}$ Efficiency η^T_{CC-CS}	36 MW 99.9%	100 MW 99.9%	
CI-CR	Max. cap. $P^T_{CI-CR,max}$ Efficiency η^T_{CI-CR}	36 MW 99.9%		

While maximum capacities and transmission capacities are sufficient for the network flow, we also need the line and pipeline lengths, reactances $X_t^{T,el}$ and the pressure drops at maximum heat and gas load ($\Delta p_{t,\,max}^{T,g}$, $\Delta p_{t,\,max}^{T,h}$) for the power flow calculations (Table 3). The normalised power–pressure drop relation (Table A1) is denormalised using the maximum capacities (Table 2) and the corresponding maximum pressure drops (Table 3).

Table 3. Lengths, reactances and pressure drops for the power flow calculations.

	Length l_t^T	Reactance $X_t^{T,el}$	Pressure Drop Gas $\Delta p_{t,\,max}^{T,g}$	Pressure Drop Heat $\Delta p_{t,\,max}^{T,h}$
	km	*W/km*	*mbar*	*mbar*
CI-CC	2.5	0.0729	40.5	119.1
CI-CS	5.0	0.0729	40.5	119.1
CC-CS	7.5	0.0729	40.5	
CI-CR	10.0	0.0729		

For any cell electricity and domestic or process heat, time series are created based on the annual demand E_l^L (Table 4). In total, 80% of the process heat is considered to be waste heat and can be further utilised for domestic heating. To create time series with a resolution of 15 min, the load profile generator oemof.demandlib [54] was used. For any cell, a maximum potential for PV and wind RES was assumed. Time series were obtained using renewables.ninja (location: latitude: 47.84, longitude: 16.54; year 2014) [55,56].

Table 4. Annual demand, annual RES potentials and the corresponding maximum power per cell.

Cell			Electricity	Domestic Heat	Process Heat	PV	Wind
CC	Ann. Demand E_{CC}^L	GWh	137.5	405.0		31.8	
	Max. Power $P_{CC,max}^L$	MW	26.1	162.2		62.5	
CS	Ann. Demand E_{CS}^L	GWh	110.0	315.0		65.5	
	Max. Power $P_{CS,max}^L$	MW	20.9	140.4		50	
CI	Ann. Demand E_{CI}^L	GWh	220.0		72.0	130.9	
	Max. Power $P_{CI,max}^L$	MW	52.8		22.1	100	
CR	Ann. Demand E_{CR}^L	GWh	82.5	180.0		49.1	697.1
	Max. Power $P_{CR,max}^L$	MW	17.6	92.5		37.5	330

4.2. Results

The results show two basic, but different findings. The total CExC-expenditures and total installed capacities show only minor differences for both cases. Nevertheless, the capacities of the installed components in the individual cells differ significantly from the NF to PF case.

The largest deviations occur in the capacities of heat pumps, CHP, TES and batteries in the well meshed CC and CS cells. Nevertheless, summed up over all cells, the installed conversion unit capacities differ only marginally (see gap in Table 5). The biggest difference in total installed capacity is for the CHP plant in CC. In most cases lower installed capacities are obtained with the NF model than with the PF case. The same applies to the installed storage capacities (Table 6). Here, the power flow model provides the lower installed capacities, except for the battery.

In the poorly interconnected cells such as CR or the process heat production the installed capacities hardly differ, neither in the conversion units nor in the storages. Overall, apart from process heat production where gas boilers and resistance heaters are used, only exergy-efficient technology such as CHP and heat pumps are used for domestic heat production.

Table 5. Installed conversion unit capacities $P^C_{c,inst}$ and RES capacities $P^R_{r,inst}$.

		CI	CC	CS	CR	Total	Gap
		MW	**MW**	**MW**	**MW**	**MW**	**MW**
Gas boiler PH	NF PF	22.1 22.1				22.1 22.1	0.0
Resistance heater PH	NF PF	20.8 20.8				20.8 20.8	0.0
Heat pump	NF PF		163.0 138.8	145.4 171.6	240.2 240.0	548.6 550.4	+1.8
Biomass CHP	NF PF		7.1 11.0			7.1 11.0	+3.9
Fuel Cell	NF PF				20.0 20.0	20.0 20.0	0.0
Electrolyser	NF PF				66.3 66.1	66.3 66.1	−0.2
Wind	NF PF				214.9 215.0	214.9 215.0	+0.1
PV	NF PF	100 100	62.5 62.5	50 50		212.5 212.5	0.0

Table 6. Installed storage capacities $P^S_{s,inst}$.

		CI	CC	CS	CR	Total	Gap
		MWh	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**
Battery	NF PF	22.0 22.0	96.3 162.5	73.1 6.9	443.3 444.8	634.7 636.2	+1.5
TES	NF PF		1340.0 1728.8	1625.2 1219.7	8614.2 8614.2	11579.4 11,563.6	−15.8
H_2 storage	NF PF				13,474.0 13,461.2	13,474.0 13,461.2	−12.8

For operational analysis and comparison, we apply statistical methods on the time series of the installed components. The parameters calculated for conversion units, powerlines, and pipes include the mean power $P^X_{x,m}$, the minimum power $P^X_{x,min}$, the maximum power $P^X_{x,max}$ and the median power $P^X_{x,md}$. Additionally, we calculated the capacity factor $c^X_{x,F}$. For the storages we carried out the same calculations using the state of energies (*SOE*). Instead of the capacity factor, we calculated the number of annual storage cycles $c^X_{x,SC}$. The results are presented in Tables 7–9.

The data shows comparable capacity factors for the NF and PF case. Capacity factors for most conversion units and RES range from 0.05 to 0.26. Exceptional is only the gas burner with 0.39 and the gap for the biomass CHP between the NF and PF case. For all conversion units except for the process heat gas boiler and the heat pump in CC, median values are zero. This means that they are switched off for at least half of the time.

Storage cycles differ for all storages between NF and PF, with the exception of TES and H2-storage in CR. In the well meshed cells CI, CC and CS batteries and TES show higher storage cycles compared to CR. The mean TES' SOE ranges from 17% to 21% of its maximum SOE. For batteries, this value ranges from 49% to 62% in CC, CS and CR, and 18% to 21% in CI. The battery in CI is also the only storage that is empty for more than 50% of the time (median is zero).

Table 7. Statistical analysis of the conversion unit and RES timeseries.

			$c^C_{c,F}$	$P^C_{c,m}$	$P^C_{c,min}$	$P^C_{c,max}$	$P^C_{c,md}$
			-	*MW*	*MW*	*MW*	*MW*
CI	Gas boiler PH	NF	0.39	8.6	0.0	22.1	8.4
		PF	0.39	8.6	0.0	22.1	8.4
	Resistance heater PH	NF	0.08	1.7	0.0	20.8	0.0
		PF	0.08	1.7	0.0	20.8	0.0
	PV	NF	0.15	14.9	0.0	85.0	0.5
		PF	0.15	14.9	0.0	85.0	0.5
CC	Heat Pump	NF	0.21	34.2	0.0	163.0	0.3
		PF	0.23	31.9	0.0	138.8	3.7
	Biomass CHP	NF	0.05	0.4	0.0	7.1	0.0
		PF	0.10	1.1	0.0	11.0	0.0
	PV	NF	0.15	9.3	0.0	53.1	0.3
		PF	0.15	9.3	0.0	53.1	0.3
CS	Heat Pump	NF	0.20	29.4	0.0	145.4	0.0
		PF	0.18	30.7	0.0	171.6	0.0
	PV	NF	0.15	7.5	0.0	42.5	0.3
		PF	0.15	7.5	0.0	42.5	0.3
CR	Heat Pump	NF	0.09	21.8	0.0	240.2	0.0
		PF	0.09	21.8	0.0	240.0	0.0
	Fuel Cell	NF	0.26	6.9	0.0	26.7	0.0
		PF	0.26	6.9	0.0	26.7	0.0
	Electrolyser	NF	0.11	5.1	0.0	20.0	0.0
		PF	0.11	5.1	0.0	20.0	0.0
	Wind	NF	0.24	51.8	0.1	212.9	39.6
		PF	0.24	51.8	0.1	212.9	39.6

Table 8. Statistical analysis of the storages' SOE time series.

			$c^S_{s,SC}$	$SOE^S_{s,m}$	$SOE^S_{s,min}$	$SOE^S_{s,max}$	$SOE^S_{s,md}$
			-	*MWh*	*MWh*	*MWh*	*MWh*
CI	Battery	NF	108.1	3.9	0	22.0	0.0
		PF	135.4	4.7	0	22.0	0.0
CC	Battery	NF	131.8	50.6	0	96.3	51.7
		PF	129.2	82.5	0	162.5	79.1
	TES	NF	55.6	285.5	0	1339.8	138.7
		PF	50.9	327.8	0	1728.8	153.8
CS	Battery	NF	137.1	38.8	0	73.1	39.4
		PF	128.7	3.4	0	6.9	2.9
	TES	NF	40.0	297.3	0	1625.2	125.1
		PF	38.9	204.3	0	1219.7	32.3
CR	Battery	NF	72.4	221.9	0	443.3	212.2
		PF	72.8	277.9	0	444.8	303.0
	TES	NF	13.2	1583.5	0	8614.2	692.7
		PF	13.2	1577.5	0	8614.2	684.7
	H_2-storage	NF	4.5	8738.7	0	13,474.0	9881.4
		PF	4.5	8698.5	0	13,461.2	9823.1

Table 9. Statistical analysis of the powerline and heat pipeline time series.

		$P^T_{t,m}$	$P^T_{t,min}$	$P^T_{t,max}$	$P^T_{t,md}$
		MW	*MW*	*MW*	*MW*
CI-CC Heat	NF	11.8	0.0	20.8	13.4
	PF	13.1	0.0	20.8	10.7
CI-CS Heat	NF	6.8	0.0	20.5	6.8
	PF	5.4	0.0	20.8	6.4
CC-CS Electricity	NF	−0.1	−5.9	0.0	0.0
	PF	2.3	−16.6	18.4	1.7
CI-CC Electricity	NF	17.8	−27.2	36.0	14.7
	PF	19.1	−31.7	36.0	18.9
CI-CR Electricity	NF	−29.6	−36.0	36.0	−36.0
	PF	−29.6	−36.0	36.0	−36.0
CI-CS Electricity	NF	15.4	−21.1	36.0	11.2
	PF	13.0	−20.2	36.0	10.7

The normalised load duration curves and boxplots in Figure 4 show changes between the NF and PF model in all load flows except for the electrical stub line CI-CR. The occurring maximum values in both directions stay the same for all load flows, apart from CC-CS. The electrical line CC-CS is barely used in the NF case. The direct electricity flows from CI to CS in the NF case are partially rerouted in the PF case. This leads to higher flows through CI-CC and CC-CS and reduced flows through CI-CS. This can be seen from the shifted boxes in the box plot (Figure 4) and the changed mean values (Table 9). Those changed electricity flows also cause a better utilisation of the CI-CC heat pipeline at the expense of the CI-CS pipeline (Table 9).

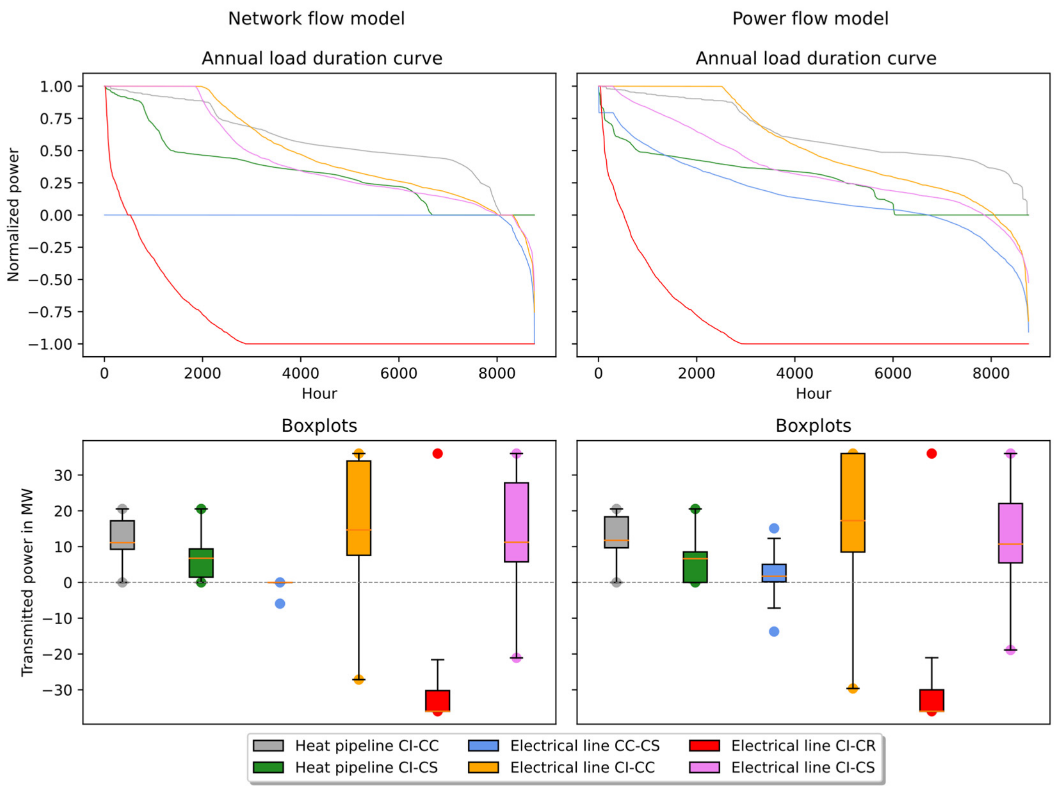

Figure 4. Normalised annual load duration curve of hourly mean values and boxplot for statistical analysis of the time series including maximum load flows in both directions.

The overall results show a total CExC-expenditures increase by 0.1% in the PF case compared to the NF case (Table 10). These are due to increased energy imports and higher infrastructure expenditures (+0.2% each). Electricity imports decrease (−5.8% compared to NF), while the biomass increases by 1.9 times (Table 11). The yields do not differ for both cases.

Table 10. CExC expenditures and yields.

	Expenditures in GWh				Yields in GWh		
	RES	**Import**	**Infrastructure**	**Total**	**Load**	**Excess**	**Total**
NW	732.1	454.8	133.3	1320.2	766.0	19.9	785.9
PF	732.2	455.7	133.6	1321.5	766.0	19.9	785.9

Table 11. CExC for the imported energy carriers.

	Electricity	Gas	Heat	Biomass
	GWh	**GWh**	**GWh**	**GWh**
NF	312.6	95.9	36.4	9.9
PF	294.5	95.9	36.4	28.9

5. Discussion and Conclusions

First, we will discuss the results and analyse the reasons for the differences between the results of the NF and PF models. Then we will close this section with a conclusion and an outlook.

5.1. Model Discussion and Comparison

The difference of only 0.1% shows that the two different load flow models only have a minor impact on the overall results. The same conversion and storage technology systems are selected for the NF and PF models, but there are differences in the installed capacities and the operating behaviour. In cells at the end of stub lines, such as CR or the process heat demand in CI, the installed capacities and the operational statistical parameters hardly change at all. The main differences occur in the well meshed cells CC and CS (compare Tables 5–9).

In NF models, the flows from one to another cell are independent from any other flow and are only restricted by the maximum capacity. In PF models all flows are linked by the power flow equations leading to specific voltage angles and pressure levels in the respective busses. Compared to the NF calculations, this leads to changes in load flows and the installed capacities of heat pumps and storages in the CC and CS cells. To fulfil the load flow equations in the PF case, the direct electricity flows from CI to CS are reduced, but they are rerouted via CI-CC and CC-CS. The CC-CS line is hardly used in the NF case (Figure 4). In the PF case, this rerouting causes an increased heat pump capacity and decreased battery and TES capacities in CS. For CC it is vice-versa.

The component with the most significant differences between NF and PF is the CHP in CC. The total installed capacity and operational statistical parameters differ between the NF and PF case like for no other component. Its capacity increases by 55% and its capacity factor doubles compared to the NF case. In the PF case the CHP is needed in times of high heat and power demand in CS and CC. Then the powerlines from CI to CC and CS are fully loaded. To satisfy the load flow equations, a flow from CC to CS must also be established, which is provided by the CHP. The load duration curve shows this state in Figure 4 with a small horizontal section at 79.4% of the maximum transmission capacity.

In the well meshed inner parts of the city (CI, CS, CC) the capacity factors of heat pumps (01.18–0.23 to 0.09) and the annual storage cycles for batteries (108.1–137.1 to 72.4–72.8) and TES (38.9–55.6 to 13.2) are higher than in cell CR for the NF and PF case (Tables 7 and 8). This is caused by the lower demand to RES potential ratio in the inner cells compared to the rural cell CR and the limited network connection of CR. Due to excess energy, this leads to lower operational expenditures for energy production and therefore allows higher infrastructure expenditures. This is analogous to results for a nodal pricing scheme in the electricity market [57].

Data in Table 10 shows that the use of the NF or PF model does not lead to significant differences in expenditures and yields. Additionally, operating and investment expenditures remain in the same order of magnitude. Even though the total expenditures for energy import only change by 0.9 *GWh* (this is equivalent to 0.2%), in the PF case there is a shift from electricity imports to biomass imports. This is caused by the biomass CHP, which must be installed in CC due to the load flow equations in the PF case.

In the real world, the high and medium voltage levels of electricity grids can be regarded as heavily meshed. Low-voltage networks are also built as meshed networks but are operated as radial networks for reasons of easier fault clearance. Large scale district heating networks are usually meshed, smaller ones are implemented as radial networks [58]. High pressure transmission gas networks are operated as radial networks, but the low pressure distribution grids are meshed [59]. Based on the results of the case studies, general recommendations for the modelling of different network levels and types can be derived (Table 12): PF models best reflect meshed networks, NF models offer insight to radial networks and stub lines.

Table 12. Proposed use of NF and PF for different energy carriers and types of networks.

		NF	PF
Electricity grids	High voltage/transmission		X
	Medium voltage/distribution		X
	Low voltage/distribution	X	
District heating networks	Large scale		X
	Small scale	X	
Gas networks	High pressure/transmission	X	
	Low pressure/distribution		X

5.2. Conclusion and Outlook

This work compares NF and PF formulations for the optimum installed conversion unit and storage capacities in a multi-cell municipal energy system model. The results show that the total CExC-expenditures for both approaches are in the same order of magnitude. However, on a cellular level there occur differences in installed storage and conversion unit capacities, especially in well-meshed cells. More detail in the model delivers more accurate results, but also requires more input parameters (which are not always available) and is computationally more expensive. For our models, computation times were in the range of one to several hours for the NF model and in the range of one to several days for the PF model (used system configuration: 32-core AMD Ryzen Threadripper 2990WX with 128GB RAM). Parametrisation of components in a multi-cell model has major impacts on computation times and result quality. Further details are provided in Appendix C.

In general, NF-like models are often used for large scale energy system models, for example in a scenario analysis for the future configuration of Great Britain's power system [60]. In the context of optimal system design, PF models are employed for electricity grid specific applications, like the long term capacity planning in Switzerland [61]. Which energy transmission representation to select for a certain model depends on the objective and purpose of the task, the available input data and the energy grid design. In radial networks, differences between an NF and PF approach will be smaller than in meshed networks.

The basic concept of CExC-minimisation was presented in [27]. In the current work we added the spatial dimension by investigating two different grid representations. Future research fields may concern the methodology and input data as well as the application of the methodology on different sectors. Improvements to the methodology include the implementation of further RES, conversion and storage technology. There is also the possibility that DSM can reduce the necessary storage capacity. Through stochastic modelling, variable RES can be modelled more realistically.

For the input data, the quality of the CExC-factors is crucial. This applies to the parameters themselves, as well as to the accuracy of the modelling. At the moment we mainly use data from the life cycle assessment database ProBas [62], a comparison to the data from other databases such as ecoinvent [63] can be beneficial. At the time of writing, all CExC-factors are constant. However, for electricity it will vary over the day and the year depending on the supply of RES. The same applies for the demand, which is currently also modelled-fixed.

The methodology is so general that future applications will cover a wide field. This ranges from small energy systems such as houses to larger energy systems such as entire countries. In our case study, we only modelled the domestic sector, which includes households, small businesses and governmental organisations. In particular, the inclusion of the transport sector (electromobility) and the industrial sector can reveal additional synergies.

Author Contributions: Conceptualisation, L.K. and T.K.; methodology, L.K.; software, P.G.; validation, L.K. and P.G.; formal analysis, R.R. and P.G.; investigation, L.K.; resources, L.K., P.G. and R.R.; data curation, L.K.; writing—original draft preparation, L.K.; writing—review and editing, T.K.; visualisation, R.R.; supervision, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AC	alternating current
CExC	cumulative exergy consumption
CHP	combined heat and power
DC	direct current
EU	European Union
HP	heat pump
MES	multi energy system
MILP	mixed integer linear programming
NF	network flow
OECD	Organisation for Economic Co-operation and Development
OPF	optimal power flow
PF	power flow
RES	renewable energy sources
TES	thermal energy storage

Nomenclature

A	cross section	r	exergy factor
B	CExC-yield	r^*	CExC-factor
B^*	CExC-expenditures	r^{*p}	equivalent periodic CExC-factor
C	storage capacity	SOE	state of energy
D	diameter	T	time period
e	specific energy	t	time series
L	length	X	reactance
m	mass	δ	density
P	power	η	efficiency
p	pressure	θ	voltage angle
R	resistance	λ	friction factor
Re	Reynolds number	τ	time step

Appendix A. Linearisation of the Heat and Gas Flows and Pressure Losses

Equation (28) is based on the Darcy-Weißbach-Equation, which describes the pressure loss of circular pipes t (Equation (A1)). L is the length of the pipe, D is the diameter of the pipe, λ is the friction factor of the pipe, $\dot{m}_t$ is the mass flow, A_t is the cross-sectional area of the pipe, ρ_t is the density of the flow, $P_t^{T,g,h}$ is the transmitted power through the pipe and e_t is the specific energy stored in the transporting fluid ($\dot{m}_t = \frac{P_t^{T,g,h}}{e_t}$). For gas flows, e_t is equal to the gross caloric value, for heat flows $e_t = c_{p,t}\Delta\Theta_t$ which is the energy between two temperature levels ($\Theta_{t,in}$, $\Theta_{t,out}$) of a supply and return flow.

$$\Delta p_T = \lambda \cdot \frac{L}{D} \cdot \frac{\rho}{2} \cdot \left(\frac{\dot{m}}{A \cdot \rho}\right)^2 = \lambda \cdot \frac{L \cdot \rho}{2 \cdot D} \cdot \left(\frac{P_t^{T,g,h}}{A \cdot \rho \cdot e}\right)^2 \tag{A1}$$

The only factor in this equation that changes between a linear flow or a turbulent flow through the pipe, is the friction factor λ_t, described in Equation (A2). In Equation (A3), Re_t is the Reynolds number, D_t is the diameter of the pipe and ε_t is the pipe roughness:

$$\text{laminar flow}: \quad \lambda_t = \frac{64}{Re_t} \tag{A2}$$

$$\text{turbulent flow}: \quad \frac{1}{\sqrt{\lambda_t}} = 2 \cdot \log\left(\frac{\varepsilon_t}{3.71 \cdot D_t} + \frac{2.51}{Re_t} \cdot \frac{1}{\sqrt{\lambda_t}}\right) \tag{A3}$$

Equation (A1) can be rearranged so that it describes the relation between pressure difference Δp_T and the power flow $P_t^{T,g,h}$. This relation we call the resistance $R_t^{T,g,h}$:

$$\Delta p_t^{T,g,h} = p_{t,in}^{T,g,h} - p_{t,out}^{T,g,h} = \frac{\lambda_t \cdot L_t}{2 \cdot D_t \cdot A_t^2 \cdot \rho_t \cdot e_t^2} \cdot R_t^{T,g,h2} = \frac{1}{R_t^{T,g,h2}} \cdot P_t^{T,g,h2} \tag{A4}$$

$$P_t^{T,g,h} = \frac{\sqrt{p_{t,in}^{T,g,h} - p_{t,out}^{T,g,h}}}{R_t^{T,g,h}} \tag{A5}$$

Since Δp_t is a root function, and the resistance $R_t^{T,g,h}$ is not constant, the relation between pressure and power flow is not linear. To be able to use MILP solvers, we need to approximate this relation by piecewise linearisation. This is done by determining the values of this function at certain grid points. In between these points, we use the convex combination methodology for interpolation [64].

We use the commercial pipe simulation software PSS SINCAL [65] to determine the grid points for the piecewise linearised function for the description of the relation between transmitted power and pressure loss. PSS SINCAL uses Equations (A1)–(A3) to calculate the pressure loss. Typical pipe dimensions and fluid properties for the heat and gas pipes are used to design model pipes. In those the power P_i is stepwise adjusted between 0 and the maximum power P_{max}. For each step i, the corresponding pressure drop Δp_i is determined. For generalisation, both values are normalized. The denormalisation can be achieved by multiplying the normalised values with the respective maximum values.

Table A1. Pipe properties.

	Heat Pipe	**Gas Pipe**
Diameter	350 mm	300 mm
Length	1000 m	1000 m
Temperature difference Supply/return	50 °C	
Gross calorific value		11 kWh/Nm^3
Pipe roughness	1 mm	0.3 mm
Max. power	50 MW	163 MW

Table A2. Normalised power and pressure loss.

Step i	Norm. Power $P_{i,n}$	Norm. Pressure Loss $\Delta p_{i,n}$	
		Natural Gas	District Heat
1	0.0	0.000	0.000
2	0.2	0.062	0.040
3	0.4	0.158	0.160
4	0.6	0.358	0.360
5	0.8	0.637	0.640
6	1.0	1.000	1.000

Appendix B. Component Properties and Equivalent Periodic CExC-Factors

Component properties and equivalent periodic CExC-factors for model input are presented in Tables A3–A5. All data is obtained from [27]. CExC-factors describe the cumulative amount of exergy needed to provide one unit of energy. Since energy and exergy are expressed in MWh, this results in a dimensionless factor (or MWh/MWh). The equivalent periodic CExC-factor describes the cumulative exergy needed to install one unit of RES, storage or conversion unit for a given period. Capacities of RES and conversion units are measured in MW, capacities of storages in MWh. In our case the investigated period is one year. Therefore, equivalent periodic CExC-factors are either $MWh/(MW \cdot a)$ (RES, conversion units) or $MWh/(MWh \cdot a)$ (storages).

Table A3. Storages.

Technology	Inflow Efficiency	Outflow Efficiency	Capacity Loss	Equivalent Periodic CExC-Factor
	-	-	$\frac{1}{s}$	$\frac{MWh}{MWh \cdot a}$
Battery	$\eta^S_{b,in} = 0.86$	$\eta^S_{b,out} = 0.86$	$\eta^S_{b,loss} = 10^{-8}$	$r^{*p,S}_b = 16.42$
TES	$\eta^S_{t,in} = 0.99$	$\eta^S_{t,out} = 0.99$	$\eta^S_{t,loss} = 2 \times 10^{-4}$	$r^{*p,S}_t = 0.42$
H2-Storage	$\eta^S_{h,in} = 0.98$	$\eta^S_{h,out} = 0.98$	$\eta^S_{h,loss} = 10^{-8}$	$r^{*p,S}_h = 1.24$

Table A4. Conversion units.

Type	Efficiency	Equivalent Periodic CExC-Factor
	-	$\frac{MWh}{MW \cdot a}$
Biomass boiler	$\eta^C_{bb,th} = 0.85$	$r^{*p,C}_{bb,th} = 8.14$
Gas boiler	$\eta^C_{gb,th} = 0.95$	$r^{*p,C}_{gb,th} = 6.83$
Heat pump	$COP^C_{hp,\ th} = 3$	$r^{*p,C}_{hp,th} = 2.60$
PEM electrolyser	$\eta^C_{pe,H_2} = 0.8$	$r^{*p,C}_{pe,H_2} = 126.68$
PEM fuel cell	$\eta^C_{pf,el} = 0.8$	$r^{*p,C}_{pf,el} = 126.68$
Resistance heater	$\eta^C_{rh,th} = 0.99$	$r^{*p,C}_{rh,th} = 1.30$
Biomass CHP	$\eta^C_{bc,th} = 0.5;\ \eta^C_{bc,el} = 0.35$	$r^{*p,C}_{bc,el} = 81.5$
Gas CHP	$\eta^C_{gc,th} = 0.5;\ \eta^C_{gc,el} = 0.35$	$r^{*p,C}_{gc,el} = 24.34$

Table A5. RES.

Type	CExC-Factor	Equivalent Periodic CExC-Factor
	$\frac{MWh}{MWh}$	$\frac{MWh}{MW \cdot a}$
PV	$r^{*R}_p = 1$	$r^{*p,R}_p = 347.6$
Wind	$r^{*R}_w = 1$	$r^{*p,R}_w = 67.1$

Appendix C. PF Equations, Multi-Cell Models and Result Quality

The main objective of this work is to minimise the CExC. In case of working with several interconnected cells, the data and properties of the components is a critical aspect. In our case study, energy grids only contribute their direct energy losses to the total CExC. In addition, the grid losses are usually small compared to the conversion losses [66]. The NF and PF load flow equations are only constraints that must be satisfied. However, they contribute indirectly to the total CExC because they affect installed capacities and operation of conversion units and storages.

In addition, the parameterisation of multi-cell models is an essential point. We assume a system configuration like in Figure A1, a two-cell system that is connected by a heat pipe. Heat source and storage are in one cell and another storage and a heat load in the other cell. Both storages have the same properties and the heat pipe has no capacity restriction. When solving this problem, the solver will always obtain the same result for the total installed storage capacity. However, the installed capacities for the individual cells as well as the time series of the heat flow in the pipe can differ for each solution, because mathematically it makes no difference in which cell the storage is located, since there is no contribution of the heat flow to the overall result. Any solution is equal to the other and anyone is mathematically correct.

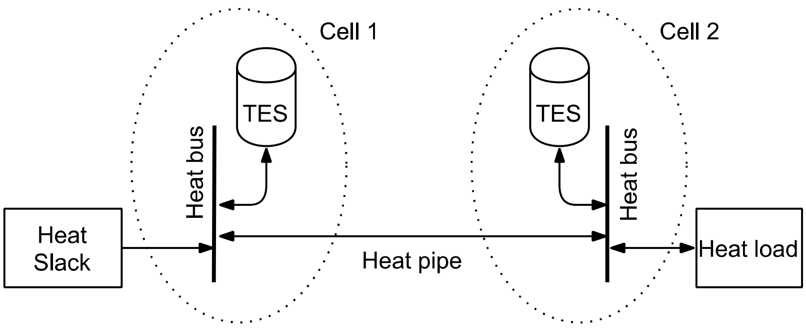

Figure A1. Example configuration for a flat optimum.

When using a piecewise linearised pressure loss formulation for the PF, things become even more complicated. Most of the modern MILP solvers such as Gurobi [67] use a two-stage solution approach. First the linear problem is solved (e.g., using simplex or barrier algorithm) and then the integer problem is solved by a branch-and-cut tree search. Feasible solutions can be obtained by a MIP-heuristic or by branching. The solver stops as soon as a MIP solution is within a predefined gap to the linear solution.

In our case the target value has a magnitude of 10^6. Storage losses per time unit are in the magnitude of 10^{-4} (TES) and 10^{-8} (battery, H_2-storage). Therefore, there might exist several different, but feasible solutions within the termination condition. Their target values may differ only slightly, but individual values may differ significantly. In our work this concerns the domestic heat supply in CS and CC, and mainly the installed storage capacities.

References

1. European Commission. *Energy Roadmap 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; 885 Brussels, Belgium, 2011*; European Commission: Brussels, Belgium, 2011.
2. Eurostat. Energy Balances. Available online: https://ec.europa.eu/eurostat/web/energy/data/energy-balances (accessed on 6 November 2019).
3. Sejkora, C.; Kienberger, T. Dekarbonisierung der Industrie mithilfe elektrischer Energie? In *15. Symposium Energieinnovation*; Technische Universität Graz: Graz, Austria, 2018.
4. Geyer, R.; Knöttner, S.; Diendorfer, C.; Drexler-Schmid, G. *IndustRiES. Energieinfrastruktur Für 100% Erneuerbare Energie in der Industrie*; Klima-und Energiefonds der österreichischen Bundesregierung: Wien, Austria, 2019.

5. Wall, G. *Exergy. A Useful Concept*; TH: Göteborg, Sweden, 1986; ISBN 9170322694.
6. International Energy Agency. *Key World Energy Statistics. Also Available on Smartphones and Tablets*; International Energy Agency: Paris, France, 2017.
7. Statistik Austria. Nutzenergieanalyse (NEA). 2017. Available online: http://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/nutzenergieanalyse/index.html (accessed on 18 January 2018).
8. Haas, R.; Panzer, C.; Resch, G.; Ragwitz, M.; Reece, G.; Held, A. A historical review of promotion strategies for electricity from renewable energy sources in EU countries. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1003–1034. [CrossRef]
9. Kriechbaum, L.; Scheiber, G.; Kienberger, T. Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges. *Energ. Sustain. Soc.* **2018**, *8*, 244. [CrossRef]
10. Sejkora, C.; Kühberger, L.; Radner, F.; Trattner, A.; Kienberger, T. Exergy as Criteria for Efficient Energy Systems—A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential. *Energies* **2020**, *13*, 843. [CrossRef]
11. Böckl, B.; Greiml, M.; Leitner, L.; Pichler, P.; Kriechbaum, L.; Kienberger, T. HyFlow—A Hybrid Load Flow-Modelling Framework to Evaluate the Effects of Energy Storage and Sector Coupling on the Electrical Load Flows. *Energies* **2019**, *12*, 956. [CrossRef]
12. Krause, T.; Kienzle, F.; Art, S.; Andersson, G. Maximizing exergy efficiency in multi-carrier energy systems. In Proceedings of the Energy Society General Meeting, Minneapolis, MN, USA, 25–29 July 2010; pp. 1–8.
13. Wall, G. Exergy tools. *Proc. Inst. Mech. Eng. A J. Power Energy* **2003**, *217*, 125–136. [CrossRef]
14. Dewulf, J.; van Langenhove, H.; Muys, B.; Bruers, S.; Bakshi, B.R.; Grubb, G.F.; Paulus, D.M.; Sciubba, E. Exergy: Its Potential and Limitations in Environmental Science and Technology. *Environ. Sci. Technol.* **2008**, *42*, 2221–2232. [CrossRef]
15. Tsatsaronis, G. Thermoeconomic analysis and optimization of energy systems. *Prog. Energy Combust. Sci.* **1993**, *19*, 227–257. [CrossRef]
16. Szargut, J.; Morris, D.R. Cumulative exergy consumption and cumulative degree of perfection of chemical processes. *Int. J. Energy Res.* **1987**, *11*, 245–261. [CrossRef]
17. Valero, A.; Lozano, M.A.; Munoz, M. A general theory of exergy saving: I. On the exergetic cost. In *Computer-Aided Engineering of Energy Systems: Vol 3. Second Law Analysis and Modelling, Proceedings of the Winter Annual Meeting of the American Society Mechan. Engin., Anaheim, CA, USA, 7–12 December 1986*; Gaggioli, R.A., Ed.; ASME: New York, NY, USA, 1986.
18. Lozano, M.A.; Valero, A. Theory of the exergetic cost. *Energy* **1993**, *18*, 939–960. [CrossRef]
19. Sciubba, E.; Bastianoni, S.; Tiezzi, E. Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy. *J. Environ. Manag.* **2008**, *86*, 372–382. [CrossRef]
20. Sciubba, E. Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems. *Exergy, Int. J.* **2001**, *1*, 68–84. [CrossRef]
21. Ziębik, A.; Gładysz, P. Analysis of the cumulative exergy consumption of an integrated oxy-fuel combustion power plant. *Arch. Thermodyn.* **2013**, *34*, 105–122. [CrossRef]
22. Wang, S.; Liu, C.; Liu, L.; Xu, X.; Zhang, C. Ecological cumulative exergy consumption analysis of organic Rankine cycle for waste heat power generation. *J. Clean. Prod.* **2019**, *218*, 543–554. [CrossRef]
23. Ertesvåg, I.S. Society exergy analysis: A comparison of different societies. *Energy* **2001**, *26*, 253–270. [CrossRef]
24. Sun, B.; Nie, Z.; Gao, F. Cumulative exergy consumption (CExC) analysis of energy carriers in China. *IJEX* **2014**, *15*, 196. [CrossRef]
25. Ukidwe, N.U.; Bakshi, B.R. Industrial and ecological cumulative exergy consumption of the United States via the 1997 input-output benchmark model. *Energy* **2007**, *32*, 1560–1592. [CrossRef]
26. Causone, F.; Sangalli, A.; Pagliano, L.; Carlucci, S. An Exergy Analysis for Milano Smart City. *Energy Procedia* **2017**, *111*, 867–876. [CrossRef]
27. Kriechbaum, L.; Kienberger, T. Optimal Municipal Energy System Design and Operation Using Cumulative Exergy Consumption Minimisation. *Energies* **2020**, *13*, 182. [CrossRef]
28. Mancarella, P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy* **2014**, *65*, 1–17. [CrossRef]

29. Böckl, B.; Kriechbaum, L.; Kienberger, T. Analysemethode für kommunale Energiesysteme unter Anwendung des zellularen Ansatzes. In *14. Symposium Energieinnovation, Proceedings of the Energie für unser Europa. 14. Symposium Energieinnovation, Graz, Austria, 10–12 February 2016*; Institut für Elektrizitätswirtschaft und Energieinnovation, Ed.; TU Graz: Graz, Austria, 2016; ISBN 978-3-85125-448-8.
30. Geidl, M.; Koeppel, G.; Perrod, P.F.; Klockl, B.; Andersson, G.; Frohlich, K. Energy hubs for the future. *IEEE Power Energy Mag.* **2007**, *5*, 24–30. [CrossRef]
31. Geidl, M.; Andersson, G. Optimal Power Flow of Multiple Energy Carriers. *IEEE Trans. Power Syst.* **2007**, *22*, 145–155. [CrossRef]
32. Mohammadi, M.; Noorollahi, Y.; Mohammadi-ivatloo, B.; Yousefi, H. Energy hub: From a model to a concept—A review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1512–1527. [CrossRef]
33. Geidl, M.; Andersson, G. Operational and topological optimization of multi-carrier energy systems. In Proceedings of the 2005 International Conference on Future Power Systems, Amsterdam, The Netherlands, 16–18 November 2005; p. 6.
34. Koeppel, G. Reliability Considerations of Future Energy Systems: Multi-Carrier Systemsand the Effect of Energy Storage. Ph.D. Dissertation, ETH Zürich, Zürich, Sweden, 2007.
35. Morvaj, B.; Evins, R.; Carmeliet, J. Comparison of individual and microgrid approaches for a distributed multi energy system with different renewable shares in the grid electricity supply. *Energy Procedia* **2017**, *122*, 349–354. [CrossRef]
36. Asmus, P. Microgrids, virtual Power Plants and Our Distributed Energy Future. *Electr. J.* **2010**, *23*, 72–82. [CrossRef]
37. Bracco, S.; Delfino, F.; Pampararo, F.; Robba, M.; Rossi, M. A mathematical model for the optimal operation of the University of Genoa Smart Polygeneration Microgrid: Evaluation of technical, economic and environmental performance indicators. *Energy* **2014**, *64*, 912–922. [CrossRef]
38. Kusch, W.; Schmidla, T.; Stadler, I. Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables. *Energy* **2012**, *48*, 153–159. [CrossRef]
39. Glavitsch, H.; Bacher, R. Optimal Power Flow Algorithms. In *Control and Dynamic Systems V41: Advances in Theory and Applications*; Leonides, C.T., Ed.; Elsevier Science: Burlington, NJ, USA, 1991; pp. 135–205. ISBN 9780120127412.
40. Frank, S.; Rebennack, S. An introduction to optimal power flow: Theory, formulation, and examples. *IIE Trans.* **2016**, *48*, 1172–1197. [CrossRef]
41. Biskas, P.N.; Ziogos, N.P.; Tellidou, A.; Zoumas, C.E.; Bakirtzis, A.G.; Petridis, V. Comparison of two metaheuristics with mathematical programming methods for the solution of OPF. *IEE Proc. Gener. Transm. Distrib.* **2006**, *153*, 16. [CrossRef]
42. Frank, S.; Steponavice, I.; Rebennack, S. Optimal power flow: A bibliographic survey I. *Energy Syst.* **2012**, *3*, 221–258. [CrossRef]
43. Geidl, M. Integrated Modeling and Optimization of Multi-Carrier Energy Systems. Ph.D. Thesis, ETH Zürich, Zürich, Sweden, 2007.
44. Purchala, K.; Meeus, L.; van Dommelen, D.; Belmans, R. Usefulness of DC power flow for active power flow analysis. In Proceedings of the IEEE Power Engineering Society General Meeting, San Francisco, CA, USA, 12–16 June 2005; pp. 2457–2462, ISBN 0-7803-9157-8.
45. Geidl, M.; Andersson, G. Optimal power dispatch and conversion in systems with multiple energy carriers. In Proceedings of the 15th Power System Computation Conference (PSSC), Liege, Belgium, 22–26 August 2005.
46. Shao, C.; Wang, X.; Shahidehpour, M.; Wang, X.; Wang, B. An MILP-Based Optimal Power Flow in Multicarrier Energy Systems. *IEEE Trans. Sustain. Energy* **2017**, *8*, 239–248. [CrossRef]
47. Xu, X.; Li, K.; Liu, Y.; Jia, H. Integrated optimal power flow for distribution networks in local and urban scales. In Proceedings of the 2016 UKACC 11th International Conference on Control (CONTROL), Belfast, UK, 31 August–2 September 2016; pp. 1–6, ISBN 978-1-4673-9891-6.
48. Unsihuay, C.; Lima, J.W.M.; de Souza, A.Z. Modeling the Integrated Natural Gas and Electricity Optimal Power Flow. In Proceedings of the IEEE Power Engineering Society General meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–7, ISBN 1-4244-1296-X.
49. Pfenninger, S.; Hawkes, A.; Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renew. Sustain. Energy Rev.* **2014**, *33*, 74–86. [CrossRef]

50. Qiu, Z.; Deconinck, G.; Belmans, R. A literature survey of Optimal Power Flow problems in the electricity market context. In Proceedings of the PES'09, IEEE/PES Power Systems Conference and Exposition, Seattle, WA, USA, 15–18 March 2009; pp. 1–6, ISBN 978-1-4244-3810-5.
51. Oemof Developer Group. *Open Energy Modelling Framework (Oemof)—A Modular Open Source Framework to Model Energy Supply Systems. Version V0.1.4*; Zenodo: Berlin, Germany, 2017.
52. Hilpert, S.; Kaldemeyer, C.; Krien, U.; Günther, S.; Wingenbach, C.; Plessmann, G. The Open Energy Modelling Framework (oemof)—A new approach to facilitate open science in energy system modelling. *Energy Strategy Rev.* **2018**, *22*, 16–25. [CrossRef]
53. United Nations (Ed.) *International Recommendations for Energy Statistics (IRES)*; United Nations: New York, NY, USA, 2017; ISBN 9789211615845.
54. Oemof Developer Group. *The Oemof Demandlib (Oemof.Demandlib)*; Zenodo: Berlin, Germany, 2016.
55. Pfenninger, S.; Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **2016**, *114*, 1251–1265. [CrossRef]
56. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239. [CrossRef]
57. Ding, F.; Fuller, J.D. Nodal, Uniform, or Zonal Pricing: Distribution of Economic Surplus. *IEEE Trans. Power Syst.* **2005**, *20*, 875–882. [CrossRef]
58. Frederiksen, S.; Werner, S. *District Heating and Cooling*; Studentliteratur: Lund, Sweden, 2013; ISBN 9789144085302.
59. Handbuch der Gasversorgungstechnik. *Logistik—Infrastruktur-Lösungen, 1. Auflage*; Homann, K., Hüwener, T., Klocke, B., Wernekinck, U., Eds.; DIV Deutscher Industrieverlag: München, Germany, 2017; ISBN 9783835672994.
60. Pfenninger, S.; Keirstead, J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. *Appl. Energy* **2015**, *152*, 83–93. [CrossRef]
61. Singh, A.; Willi, D.; Chokani, N.; Abhari, R.S. Optimal power flow analysis of a Switzerland's transmission system for long-term capacity planning. *Renew. Sustain. Energy Rev.* **2014**, *34*, 596–607. [CrossRef]
62. *ProBas*; Umwelbundesamt: Dessau-Roßlau, Germany, 2015.
63. Ecoinvent. *Ecoinvent*; Ecoinvent: Zurich, Sweden, 2020.
64. Pavić, Z. Convex combinations, barycenters and convex functions. *J. Inequal. Appl.* **2013**, *2013*. [CrossRef]
65. Siemens, A.G. *PSS®SINCAL*; Siemens AG: Munich, Germany, 2016.
66. Kriechbaum, L.; Heinrich, D.; Kienberger, T. Werkzeug zur Ermittlung der Exergieeffizienz von Fernwärmesystemen. In Proceedings of the 10. Internationale Energiewirtschaftstagung, Wien, Austria, 15–17 February 2017.
67. Gurobi Optimization. *Gurobi*; Gurobi Optimization: Beaverton, OR, USA, 2020.

13 APPENDIX B: FURTHER SCIENTIFIC PUBLICATIONS AND CONFERENCE PROCEEDINGS

[1] VOPAVA, Julia ; BÖCKL, Benjamin ; KRIECHBAUM, Lukas ; KIENBERGER, Thomas: *Anwendung zellularer Ansätze bei der Gestaltung zukünftiger Energieverbundsysteme*. In: *e & i Elektrotechnik und Informationstechnik* 134 (2017), Nr. 3, S. 238–245

[2] KRIECHBAUM, Lukas ; HEINRICH, Daniel ; KIENBERGER, Thomas: Werkzeug zur Ermittlung der Exergieeffizienz von Fernwärmesystemen. In: *10. Internationale Energiewirtschaftstagung*. Wien, 2017

[3] KRIECHBAUM, L. ; BÖCKL, B. ; VOPAVA, J. ; KIENBERGER, T.: SmartExergy – Primary Energy Efficient and Hybrid Grid Solutions for Municipal Energy Supply Systems. In: SCHULZ, Detlef (Hrsg.): *NEIS Conference 2016*. Wiesbaden : Springer Fachmedien Wiesbaden, 2017, S. 133–139

[4] BÖCKL, Benjamin ; KRIECHBAUM, Lukas ; KIENBERGER, Thomas: Analysemethode für kommunale Energiesysteme unter Anwendung des zellularen Ansatzes. In: Institut für Elektrizitätswirtschaft und Energieinnovation (Hrsg.): *14. Symposium Energieinnovation* : *Energie für unser Europa*. Graz : TU Graz, 2016

[5] BÖCKL, Benjamin ; GREIML, Matthias ; LEITNER, Lukas ; PICHLER, Patrick ; KRIECHBAUM, Lukas ; KIENBERGER, Thomas: *HyFlow—A Hybrid Load Flow-Modelling Framework to Evaluate the Effects of Energy Storage and Sector Coupling on the Electrical Load Flows*. In: *Energies* 12 (2019), Nr. 5, S. 956

Nichts geht verloren.

Alles wird nur verwandelt.

Michael Ende, Die unendliche Geschichte