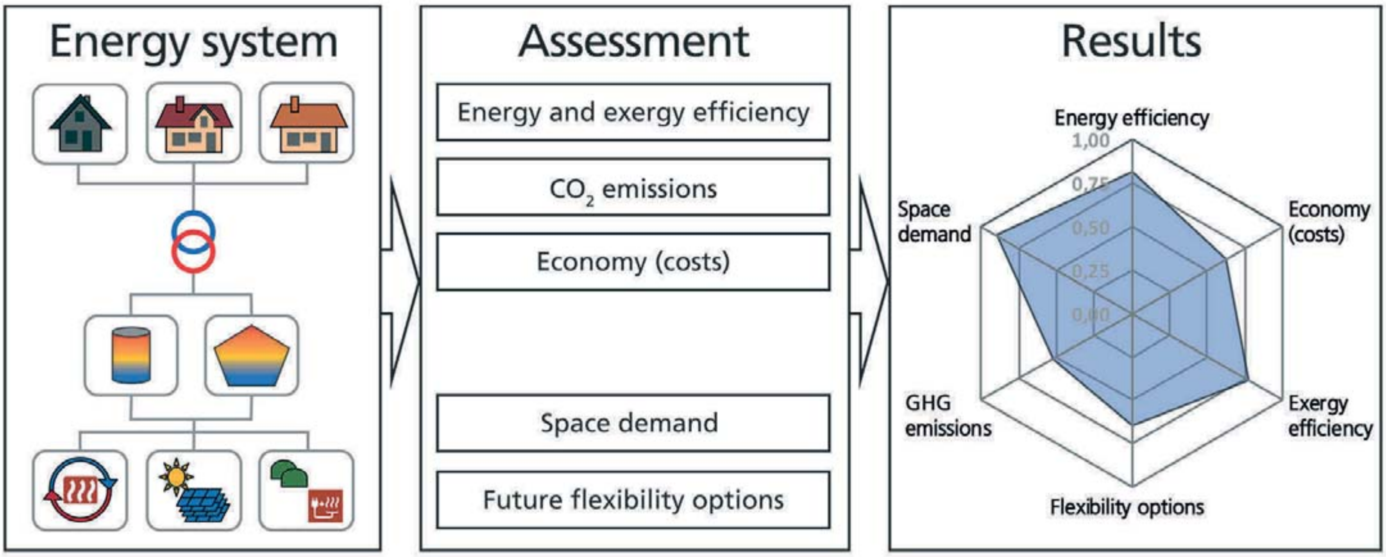
FRAUNHOFER-INSTITUT FÜR ENERGIEWIRTSCHAFT UND ENERGIESYSTEMTECHNIK IEE

Anna Marie Dagmar Kallert

Modelling and Simulation of Low-temperature District Heating Systems for the Development of an Exergy-based Assessment Method



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Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.
ISBN (Print): 978-3-8396-1435-8

D 91

Zugl.: München, TU, Diss., 2018

Druck: Mediendienstleistungen des
Fraunhofer-Informationszentrum Raum und Bau IRB, Stuttgart

Für den Druck des Buches wurde chlor- und säurefreies Papier verwendet.

Fraunhofer-Informationszentrum Raum und Bau IRB
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URL http://verlag.fraunhofer.de

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Vollständiger Abdruck der von der Fakultät für Elektrotechnik und Informationstechnik der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs (Dr.-Ing.)

genehmigten Dissertation.

Vorsitzender: Prof. Dr.-Ing. Ralph Kennel

Prüfer der Dissertation:

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Die Dissertation wurde am 19.04.2018 bei der Technischen Universität München eingereicht und durch die Fakultät für Elektrotechnik und Informationstechnik am 20.04.2018 angenommen.

Acknowledgment

This thesis would not have been possible without the guidance and the support of so many people. It is to them that I owe my deepest gratitude.

First of all, I am deeply thankful to my supervisors Dr. Dietrich Schmidt and Dr. Christina Sager-Klauß for their nice way of giving me support and guidance through all these years. Thanks for being always ready to discuss, for competent help and for granting the necessary freedom to carry out scientific work and to grow up to an always curious scientist. Thank you, Dietrich, for being my mentor.

Thank you very much to Prof. Dr. Ulrich Wagner and Prof. Dr. Folke Björk for being willing to supervise this thesis and for the very valuable remarks and contributions.

To this research several colleagues have made a major contribution. I would like to thank all my colleagues at the department of Power-Heat-Systems of the Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) and the University of Kassel for their kindly support and readiness to answer all my questions and for making possible that I could "tinker" every day with pleasure at my work. Special thanks go to Kilian Stroh, Dr. Juan Rodriguez, Dr. Andrea Schneider and Kirsten Höttges for their useful comments, elucidating discussions and help in technical issues. Many thanks go to my always hard working and enthusiastic student workers Thies Bläse, Robert Egelkamp, Lionel Freti, Nadia Florman, Mark Newton, Florian Rösel and last but definitely not least Martin Schneider.

I owe sincere thankfulness to the IEA EBC Annex TS1 und IEA EBC Annex 64 working groups for the lively and inspiring discussions. Special thanks go to Markus Blesl, Kayo Genku, Oddgeir Gudmundsson, Sabine Jansen, Andrej Jentsch, Siir Kilkis, Hongwei Li, Forrest Meggers, Ivo Martinac, Natasa Nord, Miika Rama, Ralf-Roman Schmidt, Svend Svendsen and all the others for answering all my technical questions.

I cannot give enough thanks to my family; my mother and Hartmut, grandmother and grandfather as well as my brother and his little family. Thank you for always being there for me and always supporting me with your love. Thanks to my friends, in particular Martin and Shuang, for the patient listening and in particular emotional support during these years.

Ulf, you are the balance of my everyday life, I don't know what I would have done without you.

Last but not least, I thank the German Federal Ministry of Economy and Technology as well as the Fraunhofer Society for their support in the scope of the "Fraunhofer Doktorandinnen Programm".

Abstract

The implementation of the targets of the German energy transition requires new and innovative approaches for an increased use of renewable energy sources (RES) in the heating sector. In this context, low temperature district heating (LTDH) offers new possibilities for efficient energy supply and reduced consumption of fossil fuels. LTDH allows the use of RES or excess heat, which is often available at a low temperature level. For the analysis of LTDH, the exergy analysis offers benefits since it indicates how well the thermodynamic potential of a source is used. As a result, it has to be proven that exergy is a one of the main indicators for the optimisation of heat supply on a district level. Exergy assessment does not inherently include other objectives such as maximizing the use of RES or minimizing emissions and costs, which are often of particular relevance in real implementation projects. Accordingly, a consistent exergy-based assessment method for small-scale low temperature supply systems is developed, in which energy as well as economic and sustainability aspects are brought together. As part of this work, the exergy analysis was adapted to allow the assessment of a LTDH supply in combination with additional technology and planning parameters. These parameters comprise energy efficiency, GHG emissions, full cost analysis, additional space requirements and the flexibility of energy supply in future energy systems.

To apply the method to generic case studies, an energy system has been modelled. Different centralised and decentralised supply options for new and existing buildings based on RES and fossil fuels where simulated. As centralised supply option, a LTDH grid is implemented into the model. To supply the buildings with heat, different supply units are regarded individually or in combination. As part of the decentralised options, the supply of single buildings was analysed and compared to the centralised supply options serving as reference system.

In the course of the technology comparison, different supply concepts were analysed by the application of the defined evaluation parameters. The results demonstrate that exergy analysis always leads to the conclusion that the low temperature supply is more favourable than standard solutions based on fossil fuels (e.g. condensing boilers) since it is more sensitive to the potential of the source used. Energy evaluation in turn is more sensitive to evaluate thermal losses or gains. The GHG emissions evaluation results in similar statements as the exergetic evaluation. Centralised renewable-based energy supply does in most cases lead to a higher number of technology components (e.g. borehole heat exchangers) which has a rather negative effect on the overall costs and space demand. However, in terms of flexibility options for future energy systems a LTDH grid in combination with the analysed energy supply offers great potentials.

The overall evaluation shows that the applied method is adjustable for the investigation of supply options, if increased efficiency by demand-adapted supply is desired. It is furthermore demonstrated that exergy assessment should always be combined with additional evaluation parameters to identify technological advantages, challenges and barriers of different supply technologies. However, exergy assessment as a sole evaluation method highlights the potentials of innovative low temperature district heating supply solutions on a sound thermodynamic basis. In this way, an important contribution can be made to increase the efficiency of energy supply as well as the transparency in the comparison of supply alternatives. For that reason, exergy should always be applied as a standard indicator when assessing district heating supply systems.

Zusammenfassung

Die Ziele der Energiewende erfordern innovative Ansätze für den Einsatz erneuerbarer Energien (EE) im Wärmesektor. Vor diesem Hintergrund bietet die Niedertemperatur-Fernwärme (NTFW) neue Möglichkeiten, da sie den Einsatz von EE und Abwärme erlaubt, welche häufig auf einem niedrigen Temperaturniveau zur Verfügung stehen. Auf diese Weise wird eine effiziente Versorgung bei gleichzeitiger Verringerung des Einsatzes fossiler Brennstoffe ermöglicht. Für die Analyse von NTFW stellt die exergetische Bewertung eine geeignete Methode dar, da sie aufzeigt, wie gut das thermodynamische Potential einer Energiequelle genutzt wird. Im Rahmen der Arbeit sollte daher belegt werden, dass die Exergie ein wesentlicher Bewertungsindikator für die netzgebundene Wärmeversorgung ist. Andere Ziele wie die Maximierung der Nutzung erneuerbarer Energiequellen oder die Minimierung von Emissionen und Kosten sind jedoch nicht explizit mit der exergetischen Bewertung verknüpft. Da diese in Umsetzungsvorhaben jedoch ein wesentliches Entscheidungskriterium darstellen, erfolgte die Erarbeitung einer umfassenden, exergie-basierten Bewertungsmethode, in die energetische und wirtschaftliche Gesichtspunkte einfließen. Die exergetische Analyse wurde in diesem Zuge um versorgungs- und planungsrelevante Parameter ergänzt. Diese Parameter umfassen Energieeffizienz, THG Emissionen und Kosten sowie Platzbedarf und Flexibilitätsoptionen bei der zukünftigen Energieversorgung.

Um die Methode auf generische Fallstudien anzuwenden, wurden zentrale und dezentrale Versorgungsoptionen auf Basis von EE und fossilen Brennstoffen für Neubauten und Bestandsgebäude modelliert und simuliert. Als zentrale Versorgungslösung diente ein thermisches Netz, welches durch ausgewählte Wärmeerzeuger gespeist wird. Die Erzeuger wurden einzeln oder in Kombination betrachtet. Als Referenzfall diente die dezentrale Einzelgebäudeversorgung.

Im Rahmen eines umfassenden Technologievergleichs wurden unterschiedliche Versorgungskonzepte unter der Verwendung der Bewertungsparameter analysiert. Die Ergebnisse der Exergieanalyse verdeutlichen, dass die Niedertemperaturversorgung im Vergleich zu Standardlösungen (z. B. Brennwertkessel) stets zu bevorzugen ist. Die Bewertung der THG führt in diesem Kontext meist zu ähnlichen Resultaten. Die energetische Bewertung ist hingegen von Vorteil bei der Identifikation von Wärmeverlusten. Die netzgebundene Energieversorgung erfordert häufig eine höhere Anzahl von Anlagenkomponenten (z. B. Erdwärmesonden), was sich nachteilig auf die Gesamtkosten und den Platzbedarf auswirken kann. Im Hinblick auf Flexibilitätsoptionen in künftigen Energiesystemen zeigt die netzgebundene Versorgung wiederum hohes Potenzial.

Die Gesamtbewertung zeigt, dass die entwickelte Methode umfassende Untersuchungen von Versorgungsoptionen erlaubt. Um technologische Vorteile, Herausforderungen und Hemmnisse verschiedener Versorgungslösungen zu identifizieren, sollte die exergetische Analyse stets mit weiteren Bewertungsparametern kombiniert werden. Dennoch zeigt ausschließlich die exergetische Bewertung Potenziale innovativer Versorgungslösungen für Niedertemperatur-Fernwärme auf einer thermodynamisch-fundierten Basis auf. Nur so kann ein wichtiger Beitrag zur Steigerung der Effizienz der Energieversorgung sowie der Transparenz beim Vergleich von Versorgungsalternativen geleistet werden. Aus diesem Grund sollte die Exergie bei der Bewertung von Fernwärmeversorgungssystemen als Standardindikator eingeführt und angewendet werden.

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1 Introduction

1.1 Background and motivation

The building sector, in particular residential buildings, is responsible for more than one third of the final energy consumption and therefore for a large amount of greenhouse gas (GHG) emissions due to the consumption of fossil fuels (Schmidt et al. 2016b; BMWI 2017a). The targets of the German energy transition (German: Energiewende), in particular in the heating sector, promote in this context innovative approaches based on renewable energy sources (RES) for energy efficient building supply (Gerhardt et al. 2015). Latest trends show that district heating (DH) supply with a continuously rising share of RES (e.g. solar thermal heat) becomes increasingly important with respect to the goals of the energy transition (BMWI 2017b). In particular low temperature district heating LTDH also referred to as "4^{th} generation district heating" (4GDH) offers new possibilities for greater efficiency of supply and reduced consumption of fossil fuels (Lund et al. 2014). LTDH enables the efficient use of RES (e.g. solar or geothermal heat) or excess heat (e.g. waste heat from industry) often available at a fairly low temperature level. In addition, locally available low temperature sources can be simultaneously integrated into the supply system which would potentially not be usable without a thermal network. The utilisation of lower temperatures generally reduces thermal losses in the system and can increase the overall efficiency of the energy supply chain on a community scale (Li et al. 2016). To achieve maximum efficiencies, not only the district heating network and the energy conversion chain needs to be optimal, also the demand side (building energy system) must be fitted to allow the use of low temperatures supplied by the thermal network. Accordingly the implementation of solutions based on large shares of renewable energies requires an adaptation of the technical and building infrastructure (Schmidt et al. 2016a).

Usually the assessment of heating supply concepts for small districts is carried out by means of the primary energetic assessment using primary energy factors f_p, which are found e.g. in the German standard (DIN V 18599-1:2016-10) or the (EnEV 2015) (Maßong 2014). The application of primary energetic assessment is aimed at the reduction of the use of fossil fuels and the maximisation of the use of renewable energy sources in buildings. Although the distinction is made between renewable and non-renewable forms of energy, renewable energies (e.g. biomass) are often not included in the final assessment. Accordingly, no assessment of the efficiency of the use of renewable energies can be made from primary energy analysis (Torío 2012; Bargel 2010; Schmidt 2012a). Furthermore this assessment is based on the first law of thermodynamics, in which the amount (quantity) of the final energy demand is multiplied by the primary energy factor. The actual quality of an energy form can only be derived by a combination of the first and second law of thermodynamics by using the physical property "exergy" (Dincer, Rosen 2013). Basically "exergy" can be described as a product of energy and "energy quality" and is that part of energy that can be consumed since it specifies the working potential of a given energy flow by taking the state of the environment into account (Tsatsaronis 2007). In this way the exergy assessment entails matching the quality levels of energy supply and demand in order to optimise the utilisation of high-value energy resources, such as combustible fuels, as well as to minimise energy losses and irreversible dissipation (internal losses) (Schmidt 2014). From this assessment approach, appropriate strategies and technologies with great potential for the use of low-valued energy sources (LowEx[1]) and a high share of renewable energies for heating of community supply systems can be derived (Torio, Schmidt 2011; Sager-Klauss 2016).

As a result the main motivation of this thesis is to contribute to a more holistic understanding of the energy conversion chain from generation to end use on district scale by using exergy analysis as an assessment parameter. In this way an important step can be made towards increased efficiency of energy supply based on RES as well as increased transparency in the comparison of supply alternatives.

1.2 Scope and aim of the thesis

The scope of the PhD thesis covers the analysis of renewable-based low temperature supply concepts on a district level. On the demand side the evaluation is focussed on the heating demand (space heating (SH)) and production of potable water hot (PWH) respectively domestic hot water (DHW)) occurring in single family houses (SFH). On the supply side the focus of the investigations is on low temperature district heating supply. Since this supply solution enables the simultaneous integration of various locally available RES, ground source heat pumps (GSHP), solar thermal collectors and Combined Heat and Power plants (CHP) are selected to be suitable energy suppliers (or heat generation units) as part of the investigation in this thesis.

The analysis of the supply concepts aims at comparing some different decentralized supply concepts that are using a heating grid and centralized supply concepts in order to elucidate the possible advantages and disadvantages of network-based supply for a cluster of new buildings[2]. The building stock is also analysed to figure out if and to what extent the low temperature supply of existing buildings based on RES is possible. "*Centralized supply*" *in this work is understood as the utilisation of a thermal network to supply the buildings. The term* "*decentralized*" *refers directly to the supplying units. In turn, the term* "*decentralised supply*" *is defined as the direct supply of the buildings, without a thermal network and without central storage units.*

For the evaluation of the supply concepts, the physical value “exergy” is used as the main assessment parameter. The thesis follows the hypothesis that the use of the concept of exergy can contribute decisively to the optimisation of heat based processes on a district level, since it indicates how well the potential of resources is being used. Exergy analysis has been found to provide the most accurate and insightful assessment of the thermodynamic features for any process as well as offering a clear, quantitative indication of both the irreversibility and the degree of correspondence between the resources used and the end-use energy flows (Torio, Schmidt 2011; Bargel 2010; Jentsch 2010; Hertle et al. 2014). In comparison to plain energy analysis, exergy based system optimisation facilitates the integration of renewable heat sources that are most often available at fairly low temperatures. But in real implementation projects other evaluation criteria such as emissions or costs are usually as important as the exploitation of the maximum potential of available energy sources (Jansen, Meggers 2016). Accordingly the exergy analysis has to be linked to other assessment parameters such as reduction of emissions or costs. The connection of the assessment parameters is made through the exergy optimization steps and verified by a technological comparison of different supply scenarios (Kallert, Schmidt 2016). In this way possible advantages but also technological challenges and barriers of the used supply technologies in low temperature district heating schemes can be pointed out.

[1] The term "LowEx" is used within the framework of research activities of the International Energy Agency (IEA) and the Federal Ministry of Economics (BMWi). It is a portmanteau from “Low” and “Exergy”.
[2] It has to be taken into account that the "new buildings" reflect a new standard from the year 2015. For simplicity, in the documentation these buildings are referred to as "new buildings".

Based of the detailed statements mentioned above ***the overall objective of the work is the development of a consistent, exergy-based assessment method for small scale low temperature supply systems in which energy as well as economic and sustainability aspects are brought together***. Furthermore it has to be proven that exergy is a central indicator for the assessment and optimisation of heat supply on a district level.

To achieve this objective, three subtasks are defined reflecting the most important topics of the work (Figure 1-1). Furthermore the subtasks contribute as milestones to the overall target of this thesis.

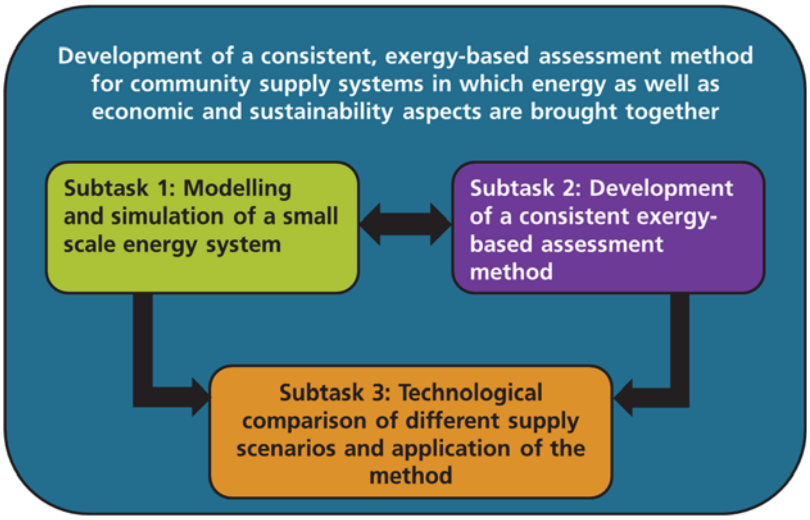


Figure 1-1: Subtasks of the thesis reflecting the most important topics for achieving the overall target of the work.

In the course of individual subtasks, the following objectives are pursued:

- **Subtask 1: Modelling and simulation of a small energy system**
  The first task is aimed at modelling and simulation of a small scale energy system, where a district heating grid is used to supply the buildings with renewable and fossil based energy. The main outcome of this task is a dynamic model for simulation of community energy systems.
- **Subtask 2: Development of a consistent exergy-based assessment method for community heating supply**
  The target of the second task is the identification of suitable assessment parameters, which complement the exergetic evaluation of low temperature district heating supply in the best way. The main outcome of this task is a robust and operationalisable technical evaluation method for analysis of different supply solutions in which energy as well as economic and sustainability aspects are brought together.
- **Subtask 3: Technological comparison of different supply scenarios and application of the method**
  As part of the third task a comprehensive technological comparison by using the model developed in subtask one it is to accomplish to demonstrate the usability of the exergy-based assessment method developed as part of subtask two. Furthermore the hypothesis is to be proven that exergy is a central indicator for the optimisation of heat based processes on a district level. Subsequently advantages and disadvantages of the energy supply as well as challenges and barriers for practical implementation are identified.

1.3 Research Questions

In order to meet the stated objectives in chapter 1.2, a number of research questions have been formulated:

- How can the exergetic assessment method contribute to a more efficient and CO_2-neutral community supply? What is the advantage of the exergetic analysis compared to conventional energetic analysis?
- Which parameters have to be combined with the exergy analysis to achieve a consistent overall picture for efficient, cost efficient and GHG emission free low temperature supply?
- What existing respectively innovative supply technologies have to be implemented or combined for future optimised energy systems on the community scale? Is it possible to supply the German building stock based on renewable energy sources? What are the minimum required temperature levels of supply for new and existing buildings?
- Which advantages and disadvantages of the technologies and technology combinations are derived from the selected assessment parameters?

These research questions will be addressed and answered in the course of the thesis. A detailed evaluation of the questions can be found in the appendix A in chapter A4.

1.4 Outline of the thesis

Next to the overall description of the thesis' aims and objectives this chapter one gives an introduction to the background and motivation. In chapter two the main fundamentals of the exergy assessment are introduced. As part of this introduction the selection of the evaluation boundaries as well as the different forms of exergy are discussed. This discussion provides the main basis for the derived method for exergetic evaluation of communities in chapter three, where a detailed method for exergy evaluation of community supply is introduced. The method is aimed at evaluation through analysis of heating supply in small residential building groups taking the climatic condition of Kassel (Germany) into account. In particular, the assessment of different supply systems from an exergetic point of view is discussed in detail. Chapter four contains a detailed description of an energy system which is modelled as part of this thesis. The model of the energy system comprises a small group of buildings, which is supplied by different energy suppliers using different energy sources by means of a thermal network. The energy system is designed based on an intensive literature research taking characteristic values of the German regulations and best practical examples into account. Chapter five covers the extension of the exergetic analysis by additional evaluation parameters. The goal here is to develop a comprehensive, exergy-based assessment method for community energy systems in which energy and economic aspects are brought together. Chapter six addresses the selection and introduction of several generic case studies which are identified by evaluation of best practice examples. Chapter seven is dedicated to a comprehensive technological comparison of different supply scenarios defined in chapter six by using the parameters defined as part of chapter five. In the course of this study, all parameters were evaluated individually or simultaneously. Furthermore advantages as well as disadvantages of the regarded supply options are discussed in detail. Moreover energy scenarios are directly compared to each other as part of a ranking. The parameters from chapter five are used for the ranking. In chapter eight the main results are summarized. Furthermore the conclusion of the work and an outlook to possible future research topics are given.

2 Fundamentals of exergy assessment

The term "exergy" was first introduced by the Slovenian professor Zoran Rant (Fritzsche et al. 1956) and is derived from the Greek words ex (from) and ergon (work). In literature a number of different designations (e.g. availablility or workability) for this property can be found (Frangopoulos 2009; Dincer, Rosen 2013; Bargel 2010).

According to (Tsatsaronis 2007) "(the) exergy of a thermodynamic system is the maximum theoretical useful work […] obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only". Resulting exergy is a thermodynamic property of both the exergy content of given energy flow and the reference environment.

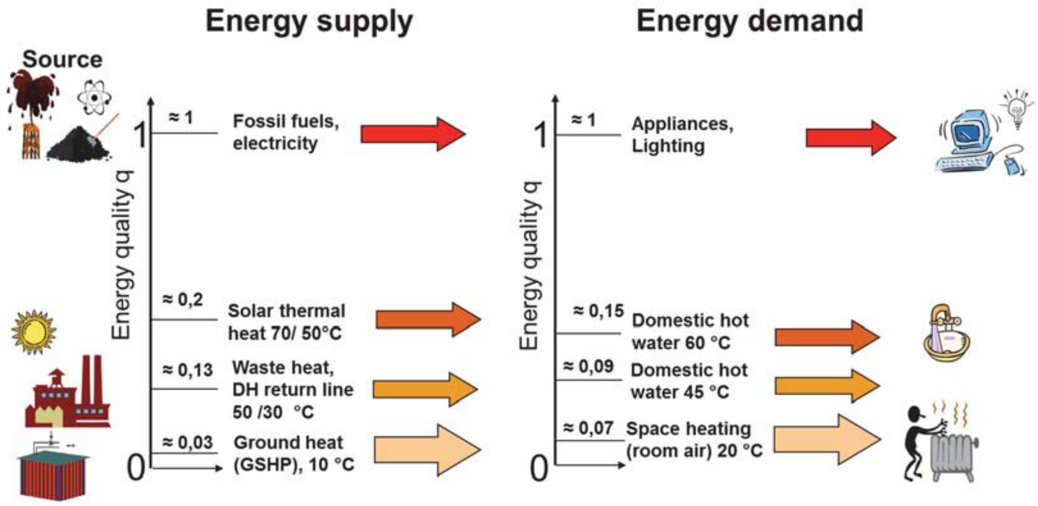


Figure 2-1: Different energy quality factors (q) of demand side and supply side for quality matched low temperature district heating supply (Kallert et al. 2016; Ala-Juusela 2004).

For evaluation of different energy systems, the exergy analysis can be used for the assessment of different forms of energy, such as work or heat. In a simplified way the different forms of energy are expressed by quality factors "q". A detailed introduction to quality factors is found as part of chapter 2.2. Basically, it can be stated that the higher the temperature level of a heat flow, compared to a reference temperature (e.g. ambient temperature), the higher the energy quality (Schmidt D. et al. 2015). Especially in connection with buildings that require only low temperatures for space heating and PWH production, the utilisation of fairly low temperatures (such as geothermal heat and solar heat) offers great possibilities for high efficient supply (see Figure 2-1) in contrast to fossil fuels or electricity. In this way exergy analysis provides critical insight into how the maximum potential of energy resources can be used. So it can contribute in a process resulting in a reduced need for high quality energy sources (e.g. fossil fuels) (Schmidt et al. 2016b).

2.1 Exergy and its role at the assessment of energy systems

In the middle of the 20th century, the concept of the exergetic analysis was developed for the assessment and optimization of thermal power plants. It was aimed to minimise the share of unused heat flows (for example waste heat), which was leading to a significant improvement in exergy efficiency (Meggers et al. 2012). In the following years, the scope of the exergetic evaluation was expanded and it was increasingly used in various disciplines and processes, such as chemical engineering (Nimkar, Mewada 2014) or optimization of production processes (Prins et al. 2005). As a result, the exergy concept became universally applicable to very different questions related to energy processes.

In recent research projects the exergetic analysis is increasingly used for the evaluation of buildings and community supply based on RES respectively LTDH. Against this background several international collaboration projects of the International Energy Agency (IEA) are carried out (IEA 2016). As part of the project "IEA EBC Annex 37 - Low Exergy Systems for Heating and Cooling" (Ala-Juusela 2004) the rational use of energy by means of facilitating and accelerating the use of low valued and environmentally sustainable energy sources for heating and cooling of buildings is aimed. The project "IEA EBC Annex 49 - Low Exergy Systems for High Performance Buildings and Communities" (Torio, Schmidt 2011), deals with concepts for reducing the exergy demand in the built environment, thus reducing CO_2 emissions from the building stock and supporting structures for setting up sustainable and secure energy systems for this sector. The latest projects of the IEA are the "IEA EBC Annex 64 - Optimised Performance of Energy Supply Systems with Exergy Principles" (Schmidt 2014) and the "IEA DHC Annex TS1 – Low Temperature District Heating for future Energy Systems" (Schmidt 2012b). As part of the "IEA EBC Annex 64" the potential of low exergy thinking on a community level as energy and cost efficient solution to achieve 100% renewable and GHG emission-free energy systems is demonstrated (Schmidt et al. 2016b). The objective of the "IEA DHC Annex TS1" is to demonstrate and validate the potential of low temperature district heating as one of the most cost efficient technology solution to achieve 100% renewable and GHG emission-free energy systems on a community level (Schmidt et al. 2016a).

Next to the international collaboration projects of the IEA a number of research projects and doctoral theses haven been published. In (Schmidt 2004) a methodology for evaluation of heat and mass transfer in buildings was developed, which is used for optimisation by minimising consumption of the necessarily supplied high quality energy, i.e. exergy. In (Bargel 2010) different technologies scenarios are assessed by using exergy as primary indicator. As part of the PhD thesis of (Jentsch 2010) an evaluation method is developed and suggested that allows a transparent exergy-based comparison of different energy supply technologies. The doctoral thesis of (Kilkis 2011) deals with the development of a strategic approach to lowering CO_2 emissions by improving the match between the supply and demand of exergy in the built environment. In (Torío 2012) exergy analysis is used for the evaluation of district heating and solar thermal supply. Here the energy generation remains unchanged and the parameters of the distribution are varied. The thesis of (Jansen 2013) deals with the evaluation of the exergy performance of different supply options for a dwelling. In particular the utilisation of heat pumps, waste-heat utilisation and cogeneration are in focus of the work. As part of (Sager-Klauss 2016) an approach for energy transition in small and medium-sized communities to create a more self-sufficient and resilient energy-system based on renewable energies was developed.

The evaluation of the research projects and doctoral theses shows that the majority are concerned with the assessment of single building supply or single supply technologies. Compared to these projects, the framework is extended for the evaluation of small neighbourhoods and different combinations of different energy suppliers are analysed as part of this thesis. In addition, further evaluation factors (e.g. costs or CO_2 emissions) are examined together with the exergetic evaluation approach. For the implementation of this thesis some of the aspects of the former research projects mentioned above are applied and adapted respectively further developed for the exergy-based analysis of generic case studies (see also chapter 3, chapter 5 and chapter 7).

2.2 Evaluation of different forms of exergy

Conforming to the First Law of Thermodynamics (FLT) the energy is a conserved quantity which can neither be produced nor destroyed in any process but only be converted into different energy forms. Furthermore it is not indicated whether conversion is possible at all within the process. The Second Law of Thermodynamics (SLT) which adds this aspect by giving the conversion a direction and giving information on the practicability of the process. The SLT differentiates two principle energy classes: energy that can be converted into any other energy form: exergy (e.g. electricity or kinetic energy) and energy which cannot be converted into other energy forms any more: anergy (which is the inert energy of the reference environment) (Sager-Klauss 2016; Dincer, Rosen 2013).

According to (Tsatsaronis 2007), different types of exergy can be differentiated. The exergy of a given system consist of:

- **Kinetic exergy** (due to the system velocity measured relative to the environment),
- **Potential exergy** (due to the system height measured relative to the environment).
- **Physical exergy** (due to the deviation of the temperature and pressure of the system from those of the environment), includes the **mechanical exergy** (associated with the system pressure) and the **thermal exergy** (associated with the system temperature)
- **Chemical exergy** (due to the deviation of the chemical composition of the system from that of the environment) includes the **reactive exergy** (associated in its calculation with chemical reactions) and **nonreactive exergy** (associated in its calculation with nonreactive processes such as expansion, compression, mixing and separation).

As part of this work the potential and kinetic exergy components are neglected, since the buildings are not moving respectively change their position over the time. As a consequence thermal exergy (heat transfer processes), mechanical exergy (pumps) and chemical exergy (combustion and mixing) are relevant for evaluation.

For assessing thermal exergy the quality factor F_Q is taken into account which is defined as the ratio between the exergy and energy of a given energy system (Torio, Schmidt 2011; Ala-Juusela 2004).

$$F_Q = \frac{Ex}{En} \tag{2-1}$$

This factor represents the maximum obtainable work from an ideal thermodynamic process at a given temperature level until a state of equilibrium is reached. If the factor is multiplied by the heat quantity $d\dot{Q}$, the thermal exergetic content of an energy stream is estimated (Torio, Schmidt 2011; Torío 2012).

$$d\dot{E}x_Q = d\dot{Q} \cdot F_Q \tag{2-2}$$

For balancing of the thermal exergy demand, it has to be considered whether a massless thermal heat flow (respectively heat flow) or a mass bound thermal heat flow (respectively mass bound flow) is analysed.

Thermal heat flows at a constant temperature can be calculated differentially as given in equation (2-3). T_{amb} is the temperature of the thermodynamic environment (see also section 2.3) and T is the temperature of the heat flow. The quality factor which is considered here is called "Carnot Factor" (CF) (Torio, Schmidt 2011). This factor is in particular applicable when the heat transfer is isothermal since the heat flow comes from a reservoir of constant temperature (Schmidt 2004; Torío 2012; Bargel 2010). This would be the case of a heat transfer where the temperature level does not vary over the course of the heat interaction (steady state conditions).

$$\dot{E}x_Q = \int d\dot{E}x_Q = \int d\dot{Q}\left(1 - \frac{T_{amb}}{T}\right) = \dot{Q} \cdot \underbrace{\left(1 - \frac{T_{amb}}{T}\right)}_{\text{Carnot factor}} \tag{2-3}$$

In case of massless heat transfers the fluid serves as a heat transfer medium and does not leave the boundaries of the considered system (e.g. solar thermal collectors or district heating pipes). Furthermore the temperature of the heat transfer medium is changing over the time which results in heat transfer processes (Rösel 2015). To calculate the exergy of these transferred heat flows, it must be taken into account that there is no reservoir of constant temperature (equation 2-4). T_{in} und T_{out} denote the respectively inlet and outlet temperature of the fluid.

$$\dot{E}x_Q = \int d\dot{E}x_Q = \int_{T_{in}}^{T_{out}} d\dot{Q}\left(1 - \frac{T_{amb}}{T}\right) \tag{2-4}$$

If its assumed that $d\dot{Q} = m \cdot c_p \cdot dT$, the following relationship arises (equation 2-5):

$$\begin{aligned}
\dot{E}x_Q &= \int_{Tin}^{T_{out}} \dot{m} \cdot c_p \cdot \left(1 - \frac{T_{amb}}{T}\right) dT \\
&= \dot{m} \cdot c_p \left[\int_{T_{in}}^{T_{out}} dT - T_{amb} \int_{T_{in}}^{T_{out}} \frac{dT}{T}\right] \\
&= \dot{m} \cdot c_p \left[(T_{out} - T_{in}) - T_{amb} \cdot \ln \frac{T_{out}}{T_{in}}\right] \\
&= \dot{m} \cdot c_p \cdot (T_{out} - T_{in}) \left[1 - \frac{T_{amb}}{(T_{out} - T_{in})} \cdot ln\left(\frac{T_{out}}{T_{in}}\right)\right] \\
&= Q\left[1 - \frac{T_{amb}}{T_{in} - T_{out}} \cdot ln\left(\frac{T_{in}}{T_{out}}\right)\right]
\end{aligned} \tag{2-5}$$

In the course of the derivation of exergy for massless heat transfer it is shown that the logarithmic temperature difference (lm) $\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$ must be considered (Baehr, Kabelac 2012). In contrast to (equation 2-4), the quality factor is related to a non - isothermal heat transfer.

Mass-bound transport occurs where the heated mass flow represents the demand (e.g. DHW production or charging of storages). In accordance with (Szargut 2005) and equation 2-6 the exergy contained in the mass flow is calculated for incompressible fluids ($c_{p,w} = const.$).

$$\dot{Ex}_Q(\dot{m}) = \dot{m} \cdot c_{p,w} \left[(T - T_{amb}) - T_{amb} \cdot ln \left(\frac{T}{T_{amb}} \right) \right] \tag{2-6}$$

In the case of DHW production or when charging a storage, the cold water (CW) entering the system with a temperature of T_{CW} is heated. The hot water leaves the system with a temperature T_{HW} at the outlet of the system. The exergy is calculated from the hot water flow leaving the balance system and the cold water flow entering the balance system (Rösel 2015; Bargel 2010; Torío 2012).

$$\Delta\dot{Ex}_Q(\dot{m}) = \dot{Ex}_Q(\dot{m}_{HW}) - \dot{Ex}_Q(\dot{m}_{CW}) \tag{2-7}$$

Using the equation 2-6 and taking in to account the exergy output of the mass flow to the system, $\Delta\dot{Ex}_Q(\dot{m})$ can be determined as follows:

$$\begin{aligned} \Delta\dot{Ex}_Q(\dot{m}) = \dot{m} \cdot c_{p,w} & \left\{ \left[(T_{CW} - T_{amb}) - T_{amb} \cdot ln \left(\frac{T_{CW}}{T_{amb}} \right) \right] \right. \\ & \left. - \left[(T_{HW} - T_{amb}) - T_{amb} \cdot ln \left(\frac{T_{HW}}{T_{amb}} \right) \right] \right\} \\ & = \dot{m} \cdot c_{p,w} \left[T_{CW} - T_{HW} - T_{amb} \cdot ln \left(\frac{T_{CW}}{T_{HW}} \right) \right] \\ & = \dot{m} \cdot c_{p,w} \cdot (T_{CW} - T_{HW}) \left[1 - \frac{T_{amb}}{T_{CW} - T_{HW}} \cdot ln \left(\frac{T_{CW}}{T_{HW}} \right) \right] \\ & = \dot{m} \cdot c_{p,w} \cdot (T_{HW} - T_{CW}) \left[1 - \frac{T_{amb}}{T_{HW} - T_{CW}} \cdot ln \left(\frac{T_{HW}}{T_{CW}} \right) \right] \end{aligned} \tag{2-8}$$

Like in the case of the derivation of the exergy assessment of the massless flows, the logarithmic mean temperature must also be used in the case of mass bound flows (Bargel 2010; Rösel 2015). With regard to the quality factor for mass bound heat flows, the analogy to the quality factor for massless thermal heat flows becomes clear.

The assessment of chemical fuels is necessary, in particular, for the assessment of different supply units, which release thermal energy through oxidation (e.g combustion). For assessment of combustion processes and electricity chemical exergy is used. Similar to the evaluation of the thermal exergy, a quality factor β_{LVH} is used (Hepbasli 2008b). The quality factor is defined as the ratio between the chemical exergy and the lower heating value (LHV) of the fuel.

$$\beta_{LVH} = \frac{Ex_{ch}^{fuel}}{LHV^{fuel}} \tag{2-9}$$

The equations introduced above are applied to the exergy assessment method, which was further developed for the evaluation of community energy supply and is introduced in detail as part of chapter 3.

2.3 The reference environment

For exergy assessment the choice of the reference environment is of fundamental importance for consistent evaluation. The reference environment is considered as the ultimate sink of all energy interactions within the analysed system and must be in equilibrium with regard to its mechanical, thermal and chemical properties[3] (Baehr, Kabelac 2012; Dincer, Rosen 2013). In recent years a lot of research activities have dealt with the development of models or discussed possible definitions for a reference environment. An overview and discussion of examples of different models of the reference environment can for example be found in (Dincer, Rosen 2013; Torío 2012; Torío et al. 2009; AGFW 2015; Sakulpipatsin 2008).

As part of this work the outdoor air, which is surrounding the buildings, is chosen as reference environment. This choice is in particular in line with (Torio, Schmidt 2011; Jansen 2013). It is assumed, that the temperature and pressure level are uniform (thermal and mechanical equilibrium). Furthermore the concentration of different chemical elements in the atmospheric air is also regarded as homogeneous (Torío 2012; Torio, Schmidt 2011). Based on these assumptions it can be concluded, that the properties of the outdoor air basically meet the requirement of the reference system and is therefore applicable for exergetic analysis. Since the properties of the investigated system are very close to those of the reference environment, the exergy analysis shows high sensitivity regarding changing conditions of the reference environment (Torio, Schmidt 2011). For that reason weather data in high resolution of one hour are implemented in the simulation model (chapter 4) and are used as part of the exergy analysis of the case studies (chapter 7).

2.4 Boundaries for exergy assessment

The definition of system boundaries depends in particular on the objective of the analysis to be carried out. Basically it has to be distinguished whether the investigations are aimed at a process evaluation of e.g. a single supply unit (for example optimisation of a heat pump) or are targeted on a comprehensive system comparison of different supply scenarios (e.g. building energy system or community supply system). For exergy assessment the definition of the boundaries for calculation have decisive influence, since exergy destruction occurs at each step of the energy conversion chain even if energy losses were ideally zero (as it is for example in the case of the heat emission system to the room air). Resulting, the choice of inconsistent boundaries for similar energy systems can lead to significantly different assessment results and misleading conclusions. For the analysis carried out in this work the methodology described in (Torio, Schmidt 2011; Torío et al. 2009; Torío 2012; Schmidt et al. 2016b) is used and adapted to the scope of this work. This method is also known as the "LowEx" approach (Schmidt et al. 2016b) and is further developed respectively adapted to community supply as part of this work. A more detailed description of the method used can be found in chapter 3.

2.5 Assessment of fossil and renewable energy sources

The clear definition of the boundaries for the assessment of different fossil and (fluctuating) renewable energy sources for heating purposes is another challenging issue as part of this thesis. The analysis of various literature sources shows that the boundaries are often not clearly defined e.g. in case of evaluating solar thermal system (Torío 2012; Torío et al. 2009; Sangi et al. 2014).

A very promising approach for the simultaneous assessment of fossil and (fluctuating) regenerative energies is the "storability criterion" introduced by (Jentsch 2010). As part of this assessment approach, a distinction is made between storable and non-storable energy forms. For evaluation,

3 It should be noted that there are two types of "equilibrium" which have to be distinguished: „Dead State" (mechanical, thermal and chemical equilibrium) and „Restricted Dead State"(mechanical and thermal equilibrium) (Bakshi 2011; Baehr, Kabelac 2012)

the primary energy carriers are used, which are affected by ambient conditions. Following assumptions are derived from the storability criterion:

- **Fuels**, such as fossil fuel (natural gas and oil) and biomass are available as stored energy. For the evaluation the chemical exergy $\mathrm{Ex_{ch}}$ is used.
- **Electricity (fossil)**, as a secondary energy carrier, is a product of previous conversion processes. The primary energy sources required for conversion are storable. For the evaluation the chemical exergy Ex_{ch} of the primary energy sources are used.
- **Electricity (renewable)**, as a secondary energy carrier, is a product of previous conversion processes and is in principle storable. The primary energy sources are not storable and have a quality of one (Hepbasli 2008a).
- **Solar radiation and geothermal energy** are not storable energy forms. For evaluation the heated fluid in the collectors respectively heat fluid in the borehole heat exchangers (BHE) from the soil is used for exergy evaluation. It is assumed that the solar radiation is a fluctuating and geothermal energy is a non-fluctuating energy source.

By distinguishing between electricity from fossil and renewable energies, the approach presented here offers a high potential for the consistent exergetic assessment of fluctuating (e.g. power from wind turbines to feed a heat pump or heat from solar thermal collectors) and non-fluctuating (e.g. geothermal heat) energy sources for covering the heating demand[4] in communities.

2.6 Assumptions and limits of the assessment method

The evaluation method developed here, is strongly aimed at evaluation of heating processes respectively supply at community level. For the evaluation of the energy suppliers, only the input of directly storable primary energy forms or non-storable energy forms are taken into account. A direct comparison of electricity and heat generation by using the approach is therefore only insufficiently possible.

Since the focus is on the assessment of a very complex energy system, a detailed exergetic process evaluation of each single system component is not intended. For example, no individual consideration of the heat pump components (e.g. compressor) is performed. Instead the occurring forms of exergy (thermal and electricity) are evaluated. Internal losses or storage effects (i.e., thermal interactions) are taken into account by the simulation. In the same way, no storage effects of the building envelope are assessed, but are also considered by the simulation model.

The exergy method is applied for evaluation of single family homes located in a climate zone in Germany (city of Kassel). For that reason no air conditioning or humidity control is regarded. As a result the part of chemical exergy, derived from differences in the humidity ratio between indoor and outdoor air, is neglected. Furthermore only natural ventilation is used in the buildings. In consequence, pressure differences can be disregarded and only thermal exergy is assessed here.

[4] As part of this thesis it is assumed, that this approach is only valid for assessment of heat supply (including auxiliary energy). This approach would have to be developed further for the assessment of electricity generation and hybrid production (for example photovoltaic thermal hybrid solar collector (P/VT)).

3 Method for exergy assessment of energy systems

The method, developed as part of this thesis, strongly aims at evaluation of heating supply in residential buildings as part of a small building group representing a small district. For the analysis the main assessment criteria and assumptions are used as they are defined in chapter 2. The energy and exergy analysis is performed following the "input-output approach" which was introduced by (Schmidt et al. 2009). As part of this approach the system is divided into several subsystems which are directly related to each other. The "input-output approach is also found in many building energy regulations such as (DIN V 18599-1:2016-10; DIN V 4701-10 2003). Accordingly the approach is a common and well proven method for (dynamic) exergy analysis of building supply and is applied in a number of research projects (e.g. (Ala-Juusela 2004; Schmidt 2004; Yildiz, Güngör 2009; Molinari 2009; Torío et al. 2009; Torío 2012)).

As part of this thesis, the boundaries were modified in such a way that the analysis of building clusters supplied by renewable-based low temperature district heating is possible (Figure 3-1). In this approach, the centralised supply units (energy suppliers, storage devices and district heating pipes) are not located inside the building envelope (see also discussion in chapter 1.2). For assessment of decentralised supply the boundaries are adapted accordingly.

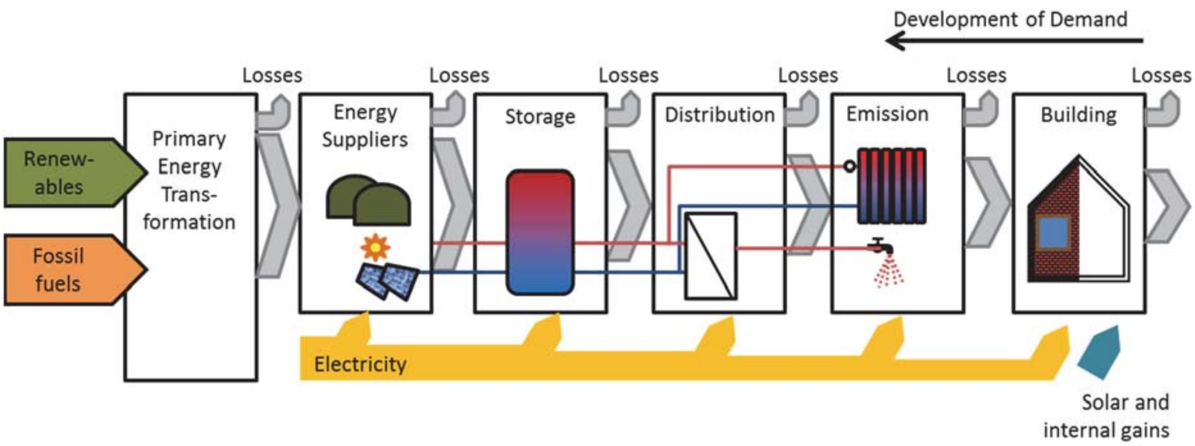


Figure 3-1: Principle sketch of energy conversion chain used for exergy assessment.

The exergetic analysis of the building cluster is carried out using the previously defined boundaries and the assumption made in chapter 2. The equations for exergy assessment of the subsystems are mainly based on those presented in (Schmidt 2004; Torío 2012; Schmidt et al. 2009; Jansen 2013). As part of this thesis the mathematical equations are revised and adapted to the targets of the thesis. In particular the mathematical description of different energy suppliers (e.g. heat pump), the storage devices (e.g. season storage) and the district heating system (e.g. substations) are further developed. The buildings are illustrated in a simplified form but include heating systems (floor heating and radiators) as well as pipes for potable water hot (PWH) supply.

3.1 General assumptions

According to the input-output approach, the consumed exergy in general for each component is expressed as follows:

$$\dot{E}x_{in,i}(t) + \dot{E}x_{out,i}(t) - \dot{E}x_{cons,i}(t) = 0 \tag{3-1}$$

The consumed exergy is the sum of the internal exergy losses and the internal exergy destruction (see also discussion in chapter 5.1):

$$\dot{E}x_{cons,i}(t) = \dot{E}x_{dest,i}(t) + \dot{E}x_{loss,i}(t) \tag{3-2}$$

In all subsystems electrical energy (auxiliary exergy) is required to run the pumps and the control units. As part of this thesis it is assumed that the electricity is attributed to the fuels (renewable or fossil) which were expended at the generation of the electricity (see discussion in chapter 2.4).

3.2 Total exergy demand of the building cluster

The final exergy demand of the entire building cluster ($\dot{E}x_{final\ dem,tot}$) is the sum of the demand of space heating (SH) and demand of PWH for each single building.

$$\dot{E}x_{final\ dem,tot}(t) = \sum_{i=1}^{n}\left(\dot{E}x_{dem,SH}\ (t) + \dot{E}x_{dem,PWH}(t)\right) \tag{3-3}$$

The subsystem “building cluster“ includes the “room air sub system”, the “building envelope” as well as the “emission system” and the production of “potable water hot (PWH)” (or alternatively also referred to as domestic hot water (DHW)). To supply the buildings (including space heating and PWH) with heat from the district heating grid respectively from decentralised energy suppliers, substations are used. The substations are found inside the thermal envelope of the buildings and inside the substations where mixing and heat transfer processes occur. Since the substation is considered as part of the heating network, these processes are discussed in chapter 3.3.

3.2.1 Building envelope and room air

The heating demand of the building from exergy point of view is calculated by taking the properties of the chosen as reference environment (outdoor air) into account (see chapter 2.3). In this way the total amount of the exergy of the heat is consumed $\left(\dot{E}x_{out,env}(t) = 0\right)$, since the buildings are in equilibrium with the environment. In contrast the energy has the same value as the final demand due to the principle of energy conservation (see also chapter 2.2). For that reason the total size of the thermal envelopes of the buildings are regarded as the system boundary of exergy assessment.

$$\dot{E}x_{in,env}(t) + \underbrace{\dot{E}x_{out,env}(t) - \dot{E}x_{con,env}\ (t)}_{=0} = 0 \tag{3-4}$$

The exergy demand for room heating $\dot{E}x_{\mathrm{dem,SH}}$ is derived according to equation (2-3):

$$\dot{E}x_{in,env}(t) = \dot{E}x_{con,env}\ (t) = \dot{Q}_{dem,SH}(t) \cdot \left(1 - \frac{T_{amb}(t)}{T_{op}(t)}\right) = \dot{E}x_{dem,SH} \tag{3-5}$$

As part of the “room air” the exergy losses between the emission system and the exergy demand of the buildings are determined. This assumption is necessary because the losses are to be assigned neither to the emission system nor to the exergy demand of the buildings (Torío 2012; Schmidt 2004). Resulting, the energy output from the emission system is equal to the energy demand, but the exergy is necessarily different due to the temperature difference responsible for the heat transfer process between the heating system (temperature at its surface T_h) and the indoor air (temperature of the room T_{op}). The surface temperature of the emission system is conventionally estimated by logarithmic mean temperature (see also discussion in chapter 2.2). As part of a simplification the surface temperatures for this study are determined by the arithmetic mean value[5] of the supply and return temperatures. This is suitable according to (Torío 2012; Recknagel, Sprenger 2012). Furthermore the solar gains and the ventilation losses are implicitly included in the assessment of the heat demand (see also chapter 4.2).

$$\dot{E}x_{con,room} = \dot{Q}_{dem,SH}(t) \cdot T_{amb}(t) \cdot \left(\frac{1}{T_{op}(t)} - \frac{1}{T_h(t)}\right) \tag{3-6}$$

In equation (3-6) the surface temperature of the emission system and the room temperature are used to calculate the exergy consumption occurring during the heat transfer process. In accordance to this equation of the temperature difference between the surface of the emission system and the room air are used.

3.2.2 Heat emission (heating system)

The process step "emission" is used to cover the determined heating demand. In the case of space heating, this takes place via the heat-transferring surfaces of the radiators or floor heating systems. According to equation (2-5) in chapter 2.2 the heating water is used as a medium for transporting heat, but the heating water always remains in the entire balancing room. It circulates in a closed system and absorbs heat at the generator by means of heat transfer (no mass exchange) and discharges it at the consumer (also no mass exchange).

$$\dot{E}x_{con,em} = \dot{m}_{em}(t) \cdot c_{p,w} \left[T_{in,em}(t) - T_{out,em}(t) - T_{amb}(t) \cdot ln\left(\frac{T_{in,em}(t)}{T_{out,em}(t)}\right)\right] \tag{3-7}$$

The heat transfer results in a change in the fluid temperature, which must be taken into account via the logarithmic temperature difference (see equation (3-7)).

3.2.3 Preparation of potable water hot (PWH)

For preparation of potable water hot (PWH) it is necessary to know the required temperature level at the tapping point and the temperature level of the potable water cold (PWC). The exergy demand is characterised by mass bound thermal exergy (see equation (2-6) in chapter 2.2). According to (VDI 2067 2012) it is assumed that PWC at a temperature level of 10 °C is heated to a temperature level (PWH) of 45 °C. The mixing processes and temperature losses are caused by a heat exchanger in the substation (see chapter 3.3).The exergy demand is calculated according to equation (3-8):

$$\dot{E}x_{PWH,dem} = \dot{m}_{PWH}(t) \cdot c_{p,w} \left[(T_{PWH}(t) - T_{PWC}(t)) - T_{amb} \cdot ln\left(\frac{T_{PWH}}{T_{PWC}}\right)\right] \tag{3-8}$$

As part of this thesis different temperature levels of district heating supply are investigated. In the event that the required supply temperature for PWH production is not achieved a resistant heater (heating rod) is regarded which uses electricity (see equation (3-29)).

[5] The arithmetic mean can be used if the condition $(T_{out,em} - T_{op})/(T_{in,em} - T_{op}) \geq 0.7$ is fulfilled. For design conditions in the radiators, i.e. supply/return and room air temperatures of 55/45/20°C resp 75/55/20 °C, this condition is fulfilled.

3.3 Distribution (District heating grid)

The investigations are aimed at the assessment of heating supply systems. As a result the evaluation is focussed on the supply line of the district heating (DH) grid. However, in the course of the modelling process (see chapter 4.6), both the return line and the supply line are taken into account simultaneously. As a result the thermal losses of the return line are implicitly considered. As part of the investigation it must be considered that the pipes are buried in the ground. The system boundary for distribution includes the piping and the substation, which transfers the heat to the building (Figure 3-2).

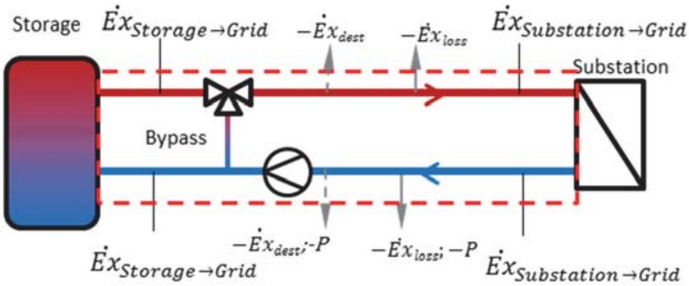


Figure 3-2: Principle sketch boundaries for exergy assessment of DH system.

Equation (3-9) shows the exergy balance for the district heating subsystem.

$$\dot{E}x_{in,DH}(t) + \dot{E}x_{ret,DH}(t) + \dot{E}x_{mix,DH}(t) + \dot{E}x_{hx,DH}(t) - \dot{E}x_{con,DH} = 0 \tag{3-9}$$

Through the pipes, the heat is transferred to the soil causing exergy losses in the system. To evaluate the district heating pipes the plug-flow approach is used (see chapter 4.6.3). This approach assumes that the circulation fluid in the pipes is divided into different fluid segments (number of segments = n). If a “new” segment enters a section of the piping system the already existing segments are moved forward (Dahm 2001).

$$\dot{E}x_{cons,DH}(t) = \sum_{i=1}^{n} \dot{m}_{i,w,DH}(t) \cdot c_{p,w} \left[\left(T_{i,DH}(t) - T_{i,DH}(t-1) \right) - T_{soil}(t) \cdot ln \frac{T_{i,DH}(t)}{T_{i,DH}(t-1)} \right] \tag{3-10}$$

Additionally pressure drops (see chapter 4.6.3) of the DH grid are covered by pumps, which require electrical energy. Exergetic consumption (destruction and losses) result in the bypass and the mixers, which regulates the supply temperature to set temperature by mixing the water from supply and return line.

$$\dot{E}x_{in,mix,sup}(t) + \dot{E}x_{in,mix,ret}(t) + \dot{E}x_{out,mix}(t) - \dot{E}x_{cons,mix}(t) = 0 \tag{3-11}$$

$$\dot{E}x_{in,mix}(t) = \dot{Q}_{in,mix}(t) \cdot \left[\left(T_{in,mix}(t) - T_{amb}(t) \right) - T_{amb}(t) \cdot ln \frac{T_{in,mix}(t)}{T_{amb}(t)} \right] \tag{3-12}$$

$$\dot{E}x_{out\ mix}(t) = \dot{Q}_{out,mix}(t) \cdot \left[\left(T_{amb}(t) - T_{out,mix}(t) \right) - T_{amb}(t) \cdot ln \frac{T_{amb}(t)}{T_{out,mix}(t)} \right] \tag{3-13}$$

Furthermore, the heat exchanger in the substation causes exergy destruction due to the temperature difference between the inlet and the outlet. Heat exchangers are modelled as adiabatic components in this thesis, i.e. no energy losses are associated to the heat exchange process. Yet, the mass flows and temperature levels at the inlet and outlet of the primary and secondary sides are different.

$$\dot{E}x_{in,hx}(t) - \dot{E}x_{out,hx}(t) - \dot{E}x_{con,hx}(t) = 0 \quad (3\text{-}14)$$

$$\dot{E}x_{in,hx}(t) = \dot{Q}_{in,hx}(t) \cdot \left[\left(T_{in,hx}(t) - T_{amb}(t)\right) - T_{amb}(t) \cdot ln\frac{T_{in,hx}(t)}{T_{amb}(t)}\right] \quad (3\text{-}15)$$

$$\dot{E}x_{out,hx}(t) = \dot{Q}_{out,hx}(t) \cdot \left[\left(T_{out,hx}(t) - T_{amb}(t)\right) - T_{amb}(t) \cdot ln\frac{T_{out,hx}(t)}{T_{amb}(t)}\right] \quad (3\text{-}16)$$

3.4 Storage units

Depending on investigated energy suppliers different types of storages are regarded which are buried in the ground. The losses depending on used type of storage device and the control strategies for charging and discharging process have strong influence on the performance of this sub system. These issues are discussed in detail as part of chapter 4.7. However for all types of storages investigated as part of the thesis it can be assumed, that storages are appliances to shift the load between energy supply and the energy demand. Correspondingly, the thermal energy stored in the system is the relevant variable for the definition of the storage system. Furthermore the exergy associated to the storage process cannot be added to the exergy consumption as it is done for other components of energy systems (Torío 2012; Schmidt et al. 2009). The general exergy balance for the storage subsystem is formulated as the sum of the charging and discharging process:

$$\dot{E}x_{ch,stor}(t) + \dot{E}x_{dis,stor}(t) = \dot{E}x_{con,stor}(t) + \dot{E}x_{stor,s}(t) \quad (3\text{-}17)$$

The exergy flows of both charging and discharging processes are calculated according to mass bound thermal exergy (see equation (2-6)). As a result the charging and the discharging processes are given as:

$$\dot{E}x_{ch,stor}(t) = \dot{m}_{ch,stor}(t) \cdot c_{p,w}\left[\left(T_{ch,in}(t) - T_{ch,ret}(t)\right) - T_{amb}(t) \cdot ln\frac{T_{ch,in}(t)}{T_{ch,ret}(t)}\right] \quad (3\text{-}18)$$

$$\dot{E}x_{dis,stor}(t) = \dot{m}_{dis,stor}(t) \cdot c_{p,w}\left[\left(T_{dis,in}(t) - T_{dis,ret}(t)\right) - T_{amb}(t) \cdot ln\frac{T_{dis,ret}(t)}{T_{dis,in}(t)}\right] \quad (3\text{-}19)$$

Both losses and storing processes are a result of the time depended temperature changes inside the tank volume. Depending on type of storage tank used different numbers (n) of layers of the stored fluid needs to be taken into account.

$$\dot{E}x_{stor}(t) = \sum_{i=1}^{n} \dot{m}_{i,stor}(t) \cdot c_{p,w}\left[\left(T_{i,DH}(t) - T_{i,DH}(t-1)\right) - T_{soil}(t) \cdot ln\frac{T_{i,DH}(t)}{T_{i,DH}(t-1)}\right] \quad (3\text{-}20)$$

The heat transfer mechanism (losses to the soil) taking part between the surface of the storage tank and the soil are formulated according to equation (2-5).

3.5 Energy supply units

As part of the technological comparison, which will be presented in chapter 7, different centralised and decentralised energy supply units are regarded. The suppliers are based on thermal energy sources or fossil fuels. As part of this conversion step, the total energy and exergy introduced into the system is considered. According to sign convention the output of energy suppliers has a negative value. In addition to the thermal energy for space and water heating, all auxiliary energy flows for pumps are also regarded here (see chapter 3.1).

3.5.1 Solar thermal collectors

Solar thermal collectors are devices installed to convert the solar radiation of the sun to thermal heat energy (collector fluid). For that reason the maximum obtainable work (exergy) from this device is the radiation of the sun characterised by using the solar source temperature which is equal to 6000 K. But according to "storability criterion" (Jentsch 2010) the working potential from solar radiation cannot directly be exploited to cover the heat demand of the buildings. The only source that is available for covering the heating demand of the buildings is the heated collector fluid ($T_{in,coll}(t)$), whose temperature is about 345 K on an annual average. Based on these assumptions the boundaries for assessment are drawn directly around the collectors. As a result estimation of exergy content of the solar thermal collectors starts by consideration of the heated fluid (refrigerant) in the thermal collectors.

$$\dot{E}x_{ST,coll} = \dot{m}_{coll}(t) \cdot c_{p,coll} \left[\left(T_{in,coll}(t) - T_{out,coll}(t) \right) - T_{amb}(t) \cdot ln \frac{T_{in,coll}(t)}{T_{out,coll}(t)} \right] \tag{3-21}$$

Additionally the approach applied here, meets the fundamental idea of exergy assessment "demand adapted supply" in its best way. The heat gained from the solar thermal collectors matches the energy demand of the building without great destruction of exergy. Another very import advantage of this approach is that direct use of solar radiation instead of degrading other high quality energy resources found in nature is advantageous (Torio, Schmidt 2011).

As part of the usage of the solar heat, auxiliary exergy (electricity) for the pumps but also heat exchanger are required to separate the solar circuit from the storage circuit (see chapter 3.1). As part of this separation mixing processes are occurring which are introduced as part of chapter 3.3.

3.5.2 Ground source heat pumps (GSHP)

The energetic input to the GSHP is the sum of the geothermal heat as well as the electricity to run the compressor. The amount of both environmental heat and electricity supplied to the GSHP is dependent on the choice of the heat pump and varies over time. Hence a summation formula is proposed to calculate the exergy output of this device. The allocation of the used environmental energy and electrical energy is carried out by using the seasonal performance factor (SPF) in the course of the simulations.

$$\dot{E}x_{GSHP,dem} = Ex_{GSHP,therm,BH} + \dot{E}x_{GSHP,el} \tag{3-22}$$

The heat from the ground is collected by using borehole heat exchangers (BHE). The refrigerant that carries heat from the ground is considered as energy source. In this procedure, only the average temperature is used, no variable temperature differences. This approach is considered being suitable since the investigations are not targeted on optimisation of the heat pump process but on assessment on this supply unit as part of the community supply system.

$$\dot{E}x_{GSHP,therm} = \dot{m}_{BHE}(t) \cdot c_{p,BHE} \left[\left(T_{in,GSHP}(t) - T_{out,GSHP}(t) \right) - T_{amb}(t) \cdot ln \frac{T_{in,BHE}(t)}{T_{out,BHE}(t)} \right] \tag{3-23}$$

As part of GSHP the electricity is directly used for covering the heat demand of the cluster. For that reason the electricity mix, represented by the quality factor β_{mix} is taken into account. By using this factor the conversion process (power plant) from fossil or renewable fuels to electricity is taken into account.

$$\dot{E}x_{GSHP,el} = P_{GSHP}(t) \cdot \beta_{mix} \tag{3-24}$$

3.5.3 Combined heat and power (CHP)

Cogeneration, or combined heat and power (CHP), describes the simultaneous production of electricity and heat by combustion of fuels such as methane. As already mentioned, the thesis is focused on exergy assessment of community heat supply. Accordingly heat controlled CHP units are regarded where the relevant output of CHP to be evaluated is the thermal energy to cover heating demand of the buildings. The energy and exergy of the natural gas (NG) are attributed to the heat. In literature a several approaches could be found (VDI 4608 2008; Hertle et al. 2014; AGFW 2014; Rosen 2008). As part of this thesis the approach according to (AGFW 2014) is applied:

$$f_{Allok,En} = \frac{Q_{th}}{Q_{th} + P_{el}} \tag{3-25}$$

Since this calculation method is directly linked to the efficiency, in the course of the evaluation, efficiency degrees η_{th}= 0.55 and η_{el}= 0.35 are used (ASUE 2011). This results in a factor for the attribution of the energy input to the thermal current of 0.61. This factor is multiplied by the fuel demand. For exergetic evaluation a formula is used, which is constructed analogously to following formula (Jentsch 2010; Bargel 2010):

$$f_{Allok,Ex} = \frac{\dot{E}x(Q_{th})}{\dot{E}x(Q_{th}) + \dot{E}x(P_{el})} \tag{3-26}$$

The exergy input of the CHP plant $\dot{E}x_{CHP}$ is calculated according to (3-27):

$$\dot{E}x_{CHP} = \dot{m}_{NG} \cdot \beta_{LHV,NG} \cdot f_{Allok,Ex} + \dot{E}x_{el,pumps} \tag{3-27}$$

3.5.4 Energy supply units using combustions processes and electricity

For exergy evaluation of energy suppliers using combustions processes (oil boiler and NG boiler), the chemical exergy $\dot{E}x_{ch}$.of the relevant fuel is taken into account. For calculation a quality factor β_{LHV}, also known as exergy coefficient, is multiplied by the lower heating value of the relevant fuel.

$$\dot{E}x_{ch} = LHV \cdot \beta_{LHV} \tag{3-28}$$

In case of the boiler it is assumed for simplification, that methane CH_4 (98 %) is used (Hepbasli 2008a; Löffler 1985). In the case of fuels, which are not clearly definable, such as coal and heating oil, empirical calculation formulas are previously required. For this reason, values taken from literature (Hepbasli 2008b) are used as part of this thesis. An overview of the fuels can be found in Table 3-1. A comparison with other literature sources (e.g. (Löffler 1985; DIN V 18599-2: 2011-08; Demirel 2016)) revealed deviations of up to 12 %. This is also due to the fact that the calorific value of the fuels depends on the region where they are exploited.

Electrical exergy is required to run the pumps and control units (auxiliary exergy) as well as the energy suppliers (GSHP, CHP and resistance heater for re-heating of PWH). For the calculation, the exergy coefficient β_{LHV} is used, which indicates the ratio of chemical exergy and LHV. According to this assumption the exergy which is available to generate electricity is attributable to combustion processes as they are to be found in the German power plant park including their conversion losses (Bargel 2010).

Table 3-1: Share of different energy carriers on German electricity mix (2014) (BDEW 2015a).

		Lignite	Coal	Natural gas	Fuel oil	Bio-mass	Nuclear	RES	Others
Share of fuels	%	25	16	10	5	7	16	19	2
Exergy coeffi-cient (β_{LHV})	-	1.06	1.09	1.04	1.07	1.15	-	-	-

According to (3-29) the exergy is calculated as a product of a quality factor β_{el} and the share of the regarded fuels (σ) entering the system. As a result, the fuel mix used in the German power plant park can be considered for this purpose (Bargel 2010).

$$\beta_{LHV,el} = \sum_{n=1}^{i} \sigma_i \beta_{fuel,i} = \sum_{n=1}^{i} \sigma_i \frac{Ex_{CH,i}}{LHV_i} \tag{3-29}$$

For the German electricity mix, an average quality factor of β_{LHV} (electricity mix) ≈1.05 can be estimated (see also discussion in chapter 2.5).

3.6 Primary energy (PER) transformation

Energy losses occurring in the conveyance, processing and transport of energy sources used to supply building energy demands are taken into account by means of primary energy factors (DIN V 18599-1:2016-10). In this way, an energy analysis of the whole energy supply chain is carried out. In case of the fossil fuels the exergy quality of the primary energy sources can be estimated in a simplified way as the product of primary energy with the corresponding exergy quality. The German electricity mix is based on different energy suppliers using different energy carriers. In order to be able to account for the actual exergetic expenditure by means of electricity, the efficiencies and exergetic quality factors of the energy carriers in the German power plant park have to be taken into account (Bargel 2010; Jentsch 2010). Taking additionally the definition of the storability “storability criterion” into account the exergy quality of the primary energy factor is estimated to be $f_{p,ex}$=1.83.

4 Modeling and simulation of an energy system

Using the simulation software TRNSYS17 (TRNSYS17 2014) a small energy system is modelled (see Figure 4-1). The model is mainly developed for the investigations as part of the technology comparison in chapter 7. The model includes ten single family houses (SFH), equipped with heating systems for space heating (SH) and instantaneous heat exchanger (HEX) for potable water hot (PWH) preparation. To supply the buildings with heat, a local heating network with substations, storages, and heat generation units consisting of: solar thermal collectors (ST), ground source heat pumps (GSHP) and natural gas-fired CHP is implemented. These different heat generation units and storages are used in the analysis according to the regarded scenarios (see chapter 6).

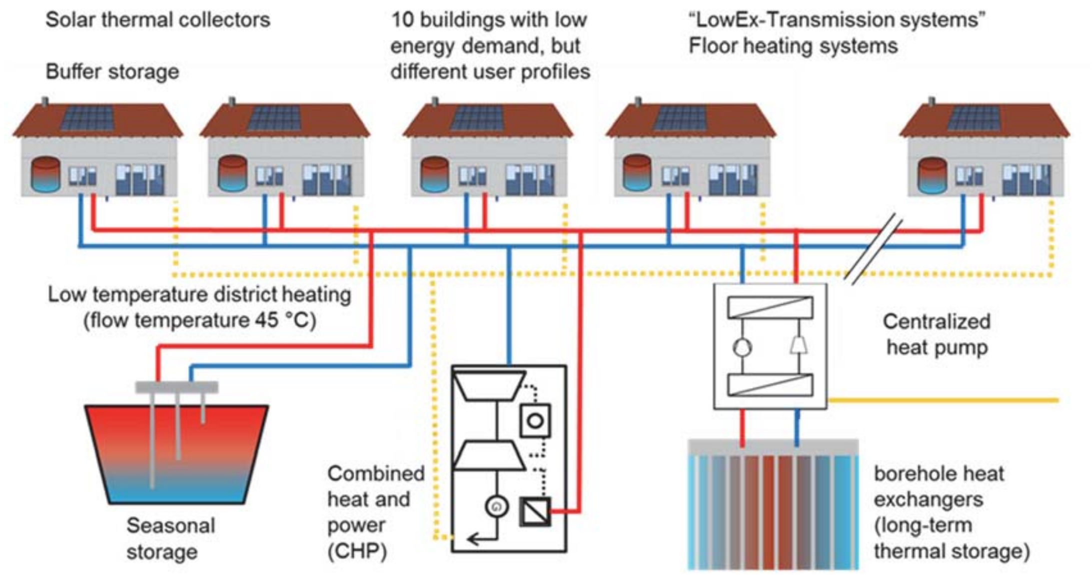


Figure 4-1: Representation of heat supply combinations for a small district heating grid connected to a building group consisting of 10 residential buildings.

As part of the following sub-chapters the dimensioning of the components implemented in the model are discussed in detail. A detailed description of the components used is found in the reports (TRANSOLAR 2015a), (TRANSOLAR 2015b) and (TRANSOLAR 2015c). Furthermore, calculation methods and values taken from the literature are explained in those reports. Unless otherwise stated, all material values are taken from (VDI 2013).

4.1 Environmental data for dynamic simulation

The environmental data (climate data and properties of the soil) has a decisive influence on the performance of the whole energy system analysed. Furthermore the exergy assessment shows high sensitivity towards the chosen reference environment (see discussion in chapter 2.3). The usage of the same environmental data for the simulation of investigated supply scenarios means assuming the same reference conditions for exergy analysis in all case studies. In consequence, the exergy performance of the building systems analysed can be compared to each other. To increase the accuracy of the simulation process the environmental data is implemented in a resolution of one hour. By using (Meteotest 2015) a weather data file for the Kassel site is created.

The weather data has a major influence on the building energy systems as well as the solar thermal collectors and are used for the regulation of the emission systems and the supplying units (load prediction). The properties of the soil are modelled using TYPE 77 (TRANSOLAR 2015a). In particular, the components, which are buried in the ground, are influenced by the soil temperature. The ground thermal conductivity is for simplicity assumed to be 1.6 W/m²K (normal soil) (Li et al. 2016).

4.2 Dimensioning of the buildings

The building group is modelled by using TYPE 56 (TRNSYS 2005). As part of this model, each building is simplified to be one thermal zone without basement. Due to this simplification, the building equipment (e.g. hydraulic loops) inside the thermal envelope is also modelled in a simplified way (for a more detailed explanation see chapter 4.6.2). For optimised use of solar radiation the buildings are oriented to the south (Kallert 2010), for that reason the window area components are assumed to be north = 7 %; south = 39 %; west / east = 19 % each.

The building data are mainly based on (Loga et al. 2015) and grouped into four building age classes. The building age classes (Table 4-1) are selected according to the introduction of the "Wärmeschutzverordnung" (engl. Heat Protection Ordinance) (BBSR 2015) which was amended three times and replaced by "Energieeinsparverordnung" (EnEV) (engl. Energy Saving Ordinance) (Maßong 2014; EnEV 2015).

Table 4-1: Properties of individual buildings for the determination of thermal behaviour (simplified according to (Loga et al. 2015)).

		Unit	Built before 1977 (1978-)	Built after 1978 (1978+)	Built after 1995 (1995+)	New buildings[6] (KfW70)
Heated living space		m²	149.48	153.82	151.67	153.52
Base of the building		m²	97.13	80.8	92.34	96
Number of storeys		-	1.72	1.6	1.61	2
Clear room height		m	2.5	2.5	2.5	2.5
Total roof surface		m²	121.07	115.14	118.32	113.2
Total window surface		m²	29.27	28.59	36.43	53.25
Door area		m²	2	2	2	2
U-value	Base slab	W/(m²K)	1.18	0.58	0.33	0.245
	Exterior wall	W/(m²K)	1.08	0.46	0.28	0.196
	Window	W/(m²K)	2.35	2.62	1.51	1.1
	Door	W/(m²K)	3	3	2	1.4
	Roof	W/(m²K)	0.73	0.41	0.28	0.14

For more realistic results, different degrees of redevelopment are assigned to the buildings. The data are taken from (Loga et al. 2015) and adapted to the targets of the thesis. It is considered that only the entire building is being renovated. In the "actual state", the U-values and the thermal bridge surcharge of the respective buildings are shown in Table 4-1. The data "Good" and "Very good" of the two reconstruction variants are found in Table 4-2.

[6] It should be noted critically that these buildings reflect an energy standard of buildings constructed before 2015.

Table 4-2: Data of the renovation options "Good" and "Very good" (Loga et al. 2015).

		Unit	Good	Very Good
U value	Base plate	W/(m²K)	1.18	0.58
	Exterior wall	W/(m²K)	1.08	0.46
	Window	W/(m²K)	2.35	2.62
	Door	W/(m²K)	3	3
	Roof	W/(m²K)	0.73	0.41
Thermal bridge surcharge		W/(m²K)	0.1	0.1

Next to the characteristics of the building envelope (U-values), the air exchange rates have a decisive influence on the thermal properties of the building. In the German regulation DIN V 18599-2 (DIN V 18599-2:2012-06) reference values are found. Since the number of inhabitants varies and different building classes are regarded in the course of the case studies, the values from regulation are adapted by interpolation to each case.

Table 4-3: Air exchange rates, including infiltration and ventilation, of the different building age classes in dependency of the amount of the heat demand (interpolated according to (DIN V 18599-2:2012-06)).

		Unit	1-2 inhabitants	3-4 inhabitants	5-6 inhabitants
-1978	Infiltration	1/h	0.56	0.56	0.56
	Ventilation	1/h	0.15	0.45	0.9
	Air exchange rate	1/h	0.7	1.0	1.5
1978+	Infiltration	1/h	0.42	0.42	0.42
	Ventilation	1/h	0.15	0.45	0.9
	Air exchange rate	1/h	0.6	0.9	1.3
1995+	Infiltration	1/h	0.24	0.24	0.24
	Ventilation	1/h	0.15	0.45	0.9
	Air exchange rate	1/h	0.4	0.7	1.1
KfW70	Infiltration	1/h	0.14	0.14	0.14
	Ventilation	1/h	0.15	0.45	0.86
	Air exchange rate	1/h	0.3	0.6	1.0

The heating load of the buildings and the simultaneity factors are an essential parameter for the design of the heating system (see chapter 4.4) and the energy suppliers (see chapter 4.8). Therefore, the calculation of the design heating load $\Phi_{HL,Bui}$ according to (DIN EN 12831 2014) is used in this work. The design heating load is the sum of transmission heat losses and ventilation heat losses.

$$\Phi_{HL,Bui} = \sum_i \Phi_{Trans,stand,i} + \sum_i \Phi_{V,i} \tag{4-1}$$

The heat transmission losses are a function of the U-Values of the buildings (see Table 4-1 resp. Table 4-2), the difference between indoor and outdoor temperature and a correction factor. Deviating from the calculation rules of the applied regulation, the mean temperature of the used weather data and the target temperatures of the user profiles are assumed (chapter 4.3). This is done in order to avoid that the building equipment is oversized (Jagnow, Wolff 2014).

$$\Phi_{T,i} = \sum_k \left(U_j + \Delta U_{TB,j}\right) \cdot A_j \cdot f_x \cdot (\vartheta_i - \vartheta_{stand}) \tag{4-2}$$

The ventilation heat loss results from the net volume of the building, the air exchange rate and the difference between room and outside air temperature. The air exchange rate is also dependent on the user type, analogous to the room temperature.

$$\Phi_{V,i} = \left(V \cdot n_{Bui} \cdot \rho_a \cdot c_{p,a}\right) \cdot (\vartheta_i - \vartheta_{stand}) \quad (4\text{-}3)$$

Since solar and internal gains in this method are not taken into account, the assumptions shown in chapter 4.3 are added in case of the modelling process. Compared to the common, normative interpretation, this approach increases the degree of accuracy and leads to an optimised design of the building energy systems (Kallert, Blaese 2016).

Due to the temporal dispersion of the heat demand of individual buildings connected to the heating network, the maximum total heating demand of the building cluster is reduced compared to the sum of the individual heating demand (space heating and PWH). This effect is also known as "simultaneity" and expressed as simultaneity factor (SF) (Winter et al. 2001).

$$SF = \frac{\sum_{i=1}^{m} \Phi_i(t)_{max}}{\sum_{i=1}^{m} \Phi_{N,i}} \quad (4\text{-}4)$$

As part of the modelling process the SF is further to be used for designing the district heating grid and the suppliers taking into account the 95%-quantile. Using the 95%-quantile means that the highest 5 % of the occurring load over the year (read from the load duration curve) are not taken into account since they are buffered by the storage devices (Winter et al. 2001). For small energy systems, the SF is typically 0.8 ...1 (Krimmling 2011; Dötsch et al. 1998). In this work the average SF is 0.89.

4.3 User behaviour: Creation of stochastic energy demand profiles

Detailed energy demand profiles for domestic housing are required for accurate analysis of demand conditions (Fischer et al. 2014; Ampatzi, Knight 2012; Widén et al. 2009). In particular when analysing small scale district heating systems, not only the characteristics of the supply system but also each inhabitant of each individual building (user) has a major impact on the whole energy demand[7]. In particular in the early stage of planning, when measured data is not available, prediction of user behaviour using randomized user profiles offers prospects for an analysis of small scale energy systems. For that reason the work is targeted on the creation of stochastic user profiles for predicting user behaviour which could be used for thermal building simulations.

For detailed holistic energy analysis the following aspects are of major importance:

- When how many residents are at home?
- When how many of those residents are active, meaning not asleep?
- When is which electricity demand caused by appliances?
- When is which thermal energy needed?
- When is how much PWH used?

For the analysis of complex energy systems all aspects need to be considered simultaneously since they are influencing each other and have significant influences on energy demand (Kallert, Blaese 2016). In literature a lot of approaches (e.g. (Capasso et al. 1994; Richardson et al. 2010; Widén, Wäckelgård 2010) for randomized user profiles are available but they are mainly focused on one

[7] This might differ, e.g. in very large cities where load balancing can occur.

or two of the aspects mentioned above. To create stochastic user profiles by taking these aspects simultaneously into account the software tool "ProfileMaker2.x" (Kallert, Blaese 2016) was developed. The VBA-Tool generates profiles of the presence and activity of the inhabitants as well as electricity and PWH profiles automatically. For the generation of electricity and occupancy profiles approaches from (Richardson et al. 2008; McKenna et al. 2015) and (Richardson et al. 2010) are applied and further developed (Kallert, Blaese 2016; Richardson et al. 2010). The PWH load is derived from (Jordan, Vajen 2000), adapted according to (VDI 2067 2012) and linked to the presence model using (McKenna et al. 2015) in order to predict tapping of PWH in a consistent way. To link the approaches from different models the calibration of probability functions are used to avoid logical errors (Blaese 2016).

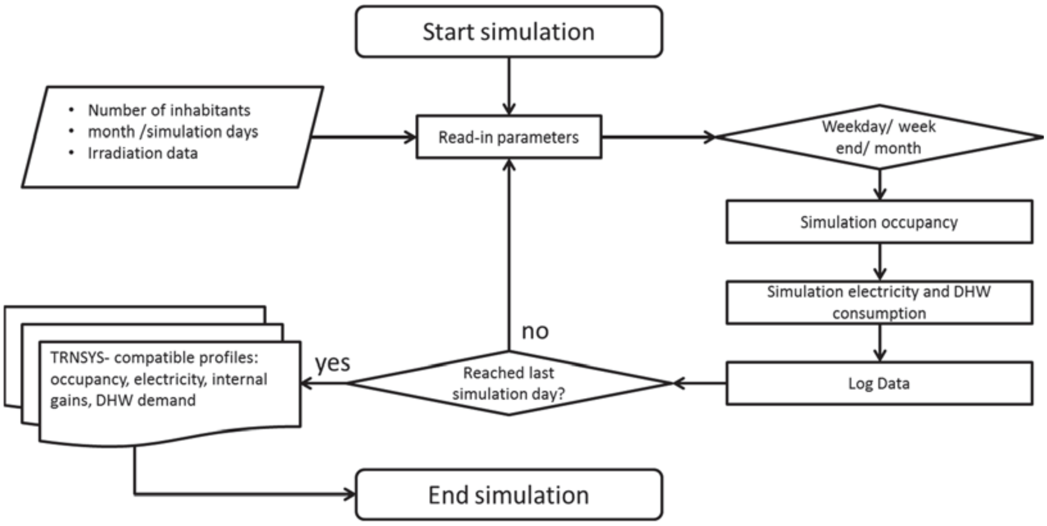


Figure 4-2: Main working principle (flow chart) of the simulation.

As part of a first step a randomized profile for "occupancy" is created taking the following possibilities into account: "inactive" (sleeping), "active" (e.g. housework, watching TV or reading) and "not at home". This profile is used for calculating the body heat emitted to the thermal zone, the PWH demand and the power demand (e.g. electricity used for appliances and lighting). Simultaneously the internal gains are calculated. Parameters, such as the number of occupants, time of day and weather data, are considered while preparing the profiles.

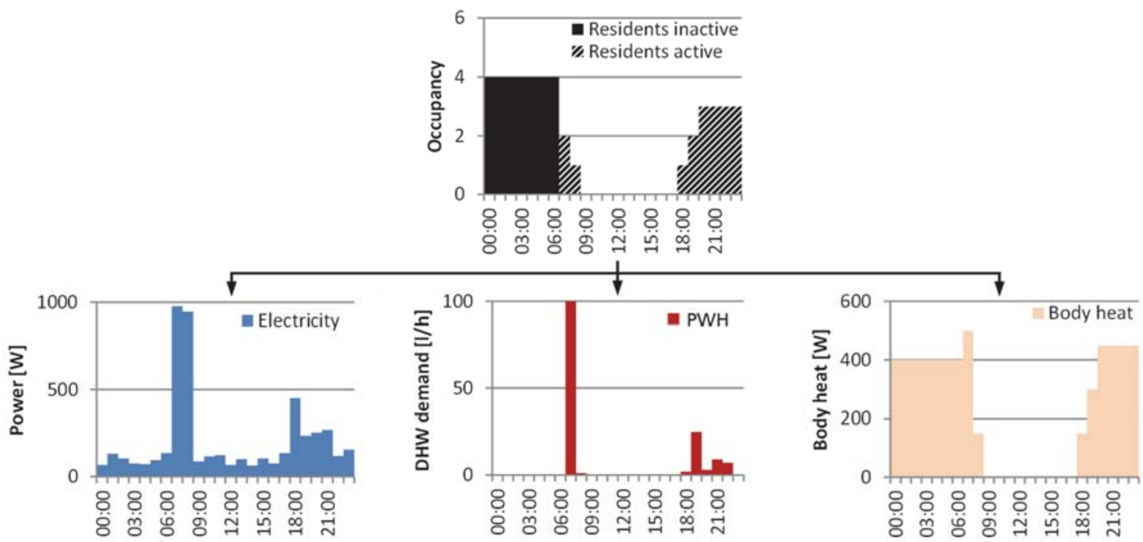


Figure 4-3: Example occupancy profile and resulting profiles (Power, PWH and Body heat) for a random day.

Next to the profiles the classification of three different user types (classes) is possible: "average", "saver" and "waster" are implemented (Table 4-4). "Average" and "saver" are equipped with night setback, which means that the room temperature is lowered by 3 °C for seven hours during the night. For each user type the number of inhabitants can be varied in order to reflect a two-person household as well as a family of four or five at the same time. Furthermore the assumptions could be used to represent a certain group of society (e.g. a young couple without children, retired couples or a single person present all day).

Table 4-4: User profiles for determination heat demand.

Building description	Name of type	Number of inhabitants	PWH (@ 45 °C)	
(-)	(-)	Pers.	l/(Pers.*d)	l/d
A1	Average	4	35	140
A3	Saver	3	20	60
L1	Saver	4	20	80
L2	Saver	5	20	100
A2	Average	3	35	105
A3	Average	4	35	140
H1	Waster	5	35	175
H2	Waster	3	60	180
H3	Waster	4	60	240
H4	Waster	5	60	300

Next to the profiles and user classification, which mainly influences the space heating demand, different PWH profiles representing different draw-off events (Table 4-5) are implemented. The routines of the VBA tool are connected to the variables "number of inhabitants" as well as "occupancy" in order to avoid logical errors.

Table 4-5: PWH demand data in accordance with (VDI 2067 2012; DIN EN 12831 2014; Viessmann 2011).

	Unit	Shower	Bath	Tab S	Tab M
Frequency	[n/day]	0.5	0.03575	7	3
Duration	[min]	5	10	1	1
Draw-off volume	[l/min]	8	14	1	6
Daily draw-off volume	[l/day]	20	5	7	18

The profiles are on an hourly basis and can be generated from one to 365 days. Furthermore it is distinguished by week day and weekend. Since the tool has been designed for generating user profiles for small scale district heating grids, a simultaneity factor is determined if the number of buildings is higher than two.

An example for heating demand for space heating and potable water hot in a micro district heating grid (Kallert et al. 2016; Kallert, Blaese 2016) which consist of 10 new buildings is shown in Figure 4-4. The corresponding building properties, which were used for this calculation are found in chapter 4.2. For the determination of the heating demand (space heating and domestic hot water production), the model of the low temperature district heating network described in chapter 4 was used. Accordingly, the weather data for the city of Kassel (Germany) was used (Meteotest 2015).

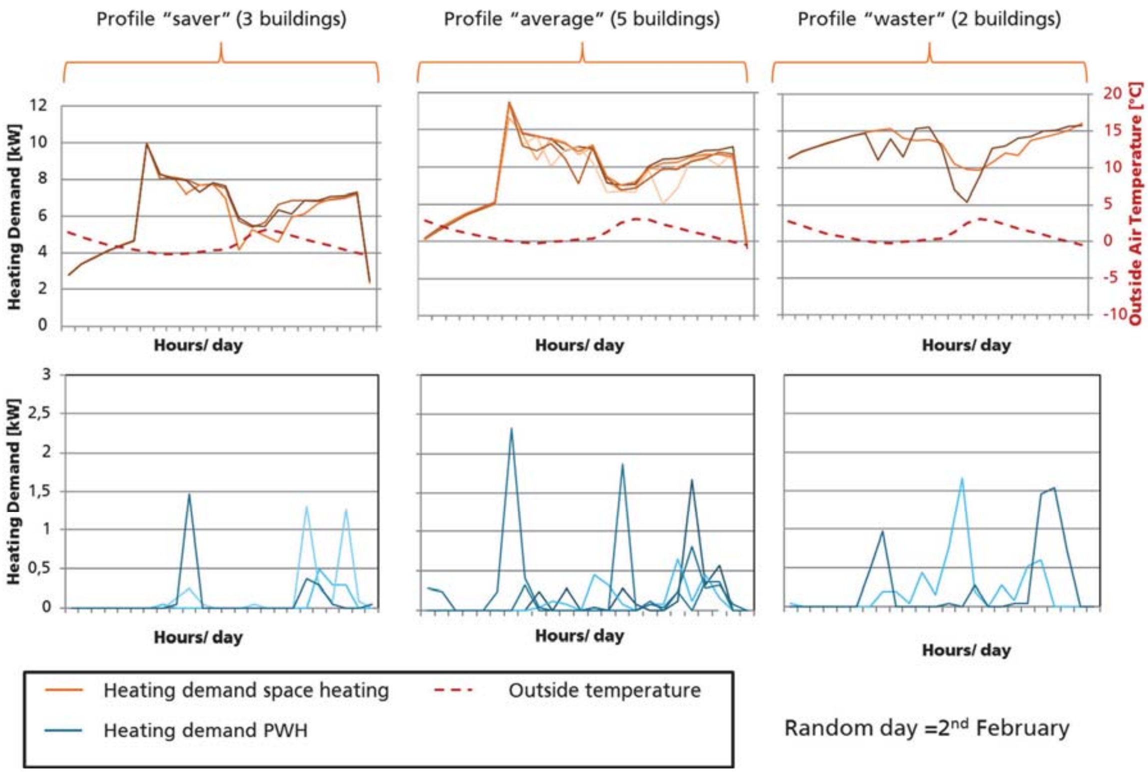


Figure 4-4: Examples for heating demand (space heating and PWH respectively DHW) for a random day (February 2nd).

The simulation results shown in Figure 4-4 is carried out for a random day (February 2nd (week day)). The variation of space heating demand depending on the type of selected user profile is represented by the orange lines. The variation of PWH demand is represented by the blue lines. The outdoor temperature is represented by the red dashed lines.

4.4 Choice and dimensioning of the emission systems

Depending on the degree of renovation and the scenarios to be examined, floor heating system and radiator system are implemented in the model (see Table 4-6).

Table 4-6: Overview of implemented heating surfaces and corresponding supply / return (S/R) temperature as a function of the buildings age classes and level of refurbishment.

Building age class	Level of refurbishment	Emission system	S/R Temperature [°C]
-1977	Existing	Radiators	75 / 65
	good	Radiators	55 / 45
	Very good	Floor heating	35 / 28
1978+	Existing	Radiators	75 / 65
	good	Radiators	55 / 45
	Very good	Floor heating	35 / 28
1995+	Existing	Radiators	75 / 65
	good	Radiators	55 / 45
	Very good	Floor heating	35 / 28
New Building	-	Floor heating	35 / 28

The radiators are modelled by using the dynamic radiator type (TYPE 362) (TRANSOLAR 2015b) and are controlled by using heating curves in order to take the weather conditions into account. The design of the radiators is done according to regulation of (DIN 4703-3 2000). The heating power is specified at standard conditions with e.g. a supply temperature of 75 °C, a return temperature of 65 °C and a room temperature (set point) of 20 °C. For heating systems with other values for supply and return temperature or for room air temperature, the radiator has to be dimensioned correspondingly larger or smaller. For this purpose, the logarithmic mean temperature is calculated according to standard conditions as well as the given supply and return temperatures:

$$\Delta T_{ln} = \frac{\vartheta_{SL} - \vartheta_{RL}}{ln\left(\frac{\vartheta_{SL} - \vartheta_i}{\vartheta_{RL} - \vartheta_i}\right)} \tag{4-5}$$

A factor is determined from the two logarithmic over-temperatures. This factor allows the conversion of the heat output of a radiator under standard conditions to radiators with deviating system parameters:

$$\frac{\Phi_{Rad}}{\Phi_N} = f = \left(\frac{\Delta T_{ln,N}}{\Delta T_{ln,Rad}}\right)^n \tag{4-6}$$

The result can be used in the following equation to determine the required mass flow.

$$\dot{m} = \frac{\Phi_{Rad}}{c_p \cdot \Delta T} \tag{4-7}$$

The floor heating systems (FH) are modelled by using the “active layer”, which is part of the TRNSYS subroutine (building group modell) TYPE56 (TRNSYS 2005). The FH is dimensioned according to (DIN EN 1264-2:2013-03) (Type A + C), since it is considered that heating pipes are laid in the screed. The heat flux density is given as:

$$\dot{q} = B \cdot a_B \cdot {a_T}^{m_T} \cdot {a_u}^{m_u} \cdot {a_D}^{m_D} \cdot \Delta\vartheta_H \tag{4-8}$$

Using the factor B the thermal conductivity of the pipes is considered. The constants a_n and their exponents describe the thermal behaviour of the pipes in the screed taking into account the properties of its construction. The factors used, as well as $\Delta\vartheta_H$ can be found in (DIN EN 1264-2:2013-03). By using the heat flux density, the required mass flow of the heating fluid $\dot{m}_H$ is estimated, which is required to supply the building according to heating load.

$$\dot{m}_H = \frac{A_F \cdot \dot{q}}{\sigma \cdot c_p} \cdot \left(1 + \frac{R_o}{R_u} + \frac{\vartheta_i - \vartheta_u}{\dot{q} \cdot R_u}\right) \tag{4-9}$$

According to (4-7) the heating capacity Φ_{FH} is calculated. The heated living space is calculated from the living area multiplied by a factor of 0.8 (Loga et al. 2015). Further, the partial heat transfer resistances of the floor are calculated as follows:

$$R_o = \frac{1}{\alpha} + R_{\lambda,B} + \frac{s_u}{\lambda_u} \tag{4-10}$$

$$R_u = R_{\lambda,ins} + R_{\lambda,ceiling} + R_{\lambda,plaster} + R_{\alpha,ceiling} \tag{4-11}$$

Both the floor heating systems as well as the radiators are controlled using weather prediction and load prediction (hysteresis). In the case of the FH, the present return temperature is compared with the return set-point temperatures. For both radiators and FH, the available room temperature is compared with set point temperature of the room air. Additional it is checked if is heating season or not (TYPE 14) (TRANSOLAR 2015a). In case of heating demand, the circulation pump of the corresponding building in the substation is activated. The control strategy (Figure 4-5) developed here, is implemented using the controlling unit (TYPE 15-2) (TRANSOLAR 2015a).

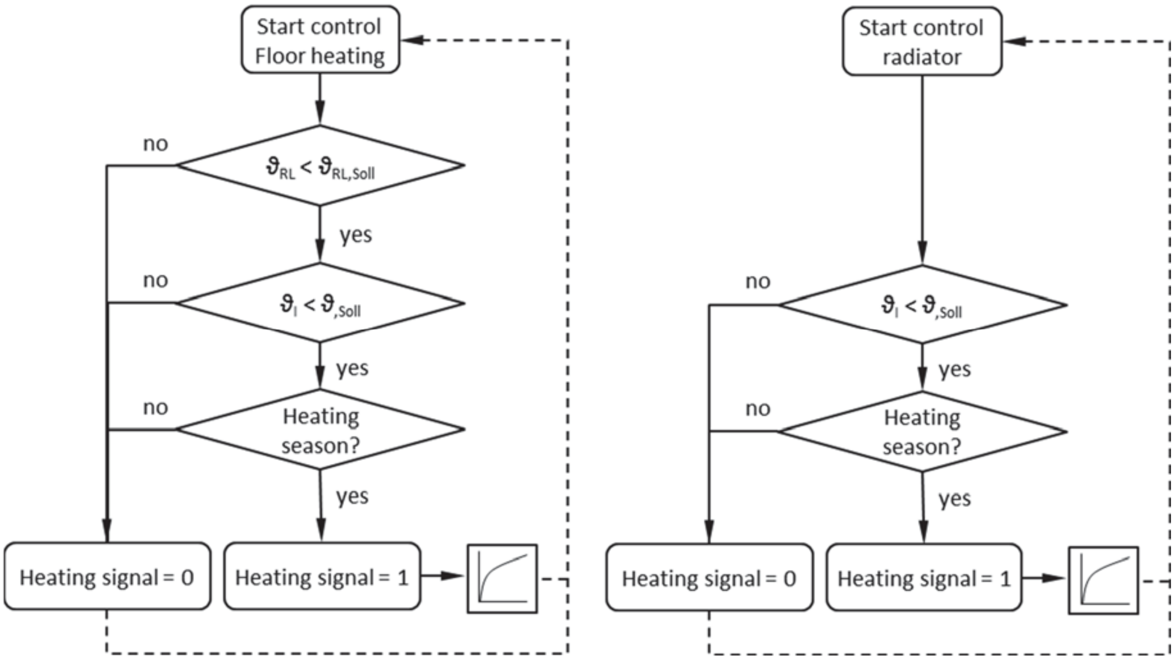


Figure 4-5: Control strategy for FHS (left) and for the radiators (right).

The set-point temperature of both the FH and the radiators are controlled using the heating curve, which is designed according to (Viessmann Deutschland GmbH 2015a).

$$\vartheta_{SL} = 0{,}55 \cdot inclination \cdot \left(\vartheta_i^{\frac{\vartheta_a}{320-\vartheta_a \cdot 4}}\right) \cdot \left((-\vartheta_a + 20) \cdot 2\right) + \vartheta_i + level \tag{4-12}$$

Basically the inclination considers the set-point temperature of the supply temperature and the level of the outdoor temperature. The temperature spread between return and supply is dependent on the emission system, which is assumed to be 5 K in case of the FH and 10 K in case of the radiators. For each building, an individual heating curve results due to the different system parameters. As it is customary in practice, in the course of the modelling process the heating curves are iteratively adapted to the considered building.

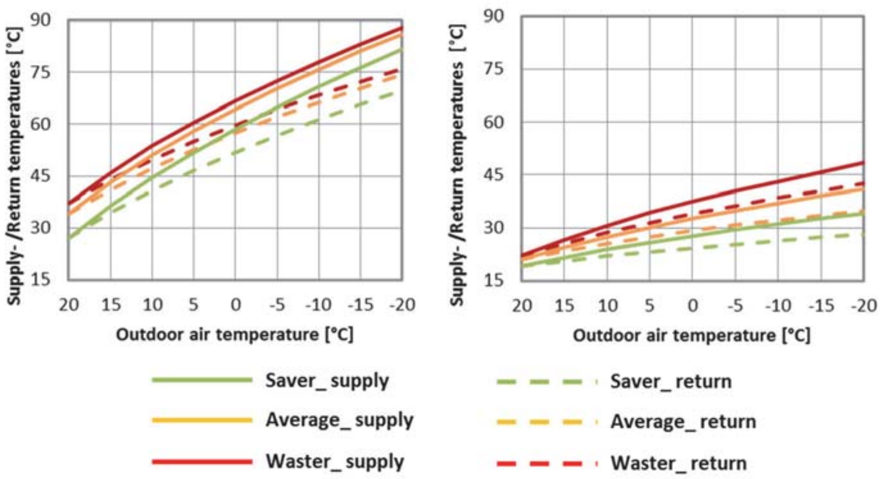


Figure 4-6: Heating curve (1978-) in actual state (left) and well renovated (right), including the different user profiles “saver”, “average” and “waster”.

An example for a heating curve of a SFH (building age 1978) for two different levels of renovation and varying user behaviour is found in Figure 4-6. It is shown that an increasing number of inhabitants (increasing energy demand) and decreasing outdoor temperature lead to higher required supply temperatures and respectively higher return temperatures. In case of renovation the supply temperatures respectively the return temperatures decrease accordingly.

4.5 Substation design and potable water hot preparation

For coupling the local low temperature DH network (see chapter 4.6) with the heating system of the building (space heating and PWH production) the buildings are equipped with a substation. The substation is directly connected to the heating network. This configuration was chosen since the direct connection is more common and is seen as the most cost-effective solution in very small local heating systems (Dötsch et al. 1998; Olsen et al. 2014).

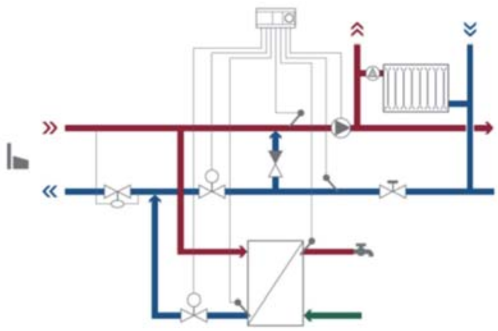


Figure 4-7: Principle for coupling the LTDH network with the heating system (Thorsen, Gudmundsson 2012).

In the substation the fluid coming from the district heating supply line is divided into three flows: heating and PWH fluid as well as by-pass (see Figure 4-7). The fluid for space heating is provided directly to the building service systems. To provide the required temperature level for space heating a bypass is used for admixture of return line from the DH grid.

For PWH production an instantaneous heat exchanger unit (IHEU) is used. The IHEU produces PWH through a plate heat exchanger (TYPE 5b) when hot water is tapped (TRANSOLAR 2015a). Using IHEU, the PWH demand of single family houses can be safely supplied at low-temperature (45 °C) without circulation pipe and without risks of legionella (Li et al. 2016; Yang 2016). In the event that the target supply temperature for PWH is not achieved the substations are equipped with an electric heating element (TYPE 6) (TRANSOLAR 2015a).

4.6 Heating loops for distribution of thermal heat

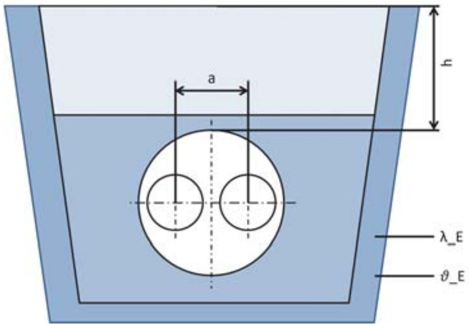
4.6.1 District heating pipes

To supply the building with heat a small low temperature district heating grid is modelled. The grid is seen as a "local district heating grid", since small-scale plants are supplying the local neighbourhood. This system variant[8] has to be differentiated from the large structure of a "conventional district heating grid". Usually conventional district heating grids are grown structures using plants of high performance, centralised character and many customers. However, these two system variants cannot be exactly separated from each other (Krimmling 2011).

The heating grid is modelled as a two-pipe system (return and supply line) with heating water as

[8] In general heating networks should not be understood as a "technology variant". It is a "system variant" which is mainly characterized by the supplying technologies, the characteristics of the buildings respectively the customers and the network parameters.

heat transfer medium. As network topology a radial network is selected. Since this topology is normally used in local low temperature district heating grids and often has the smallest route length in comparison to other topologies (REHAU AG 2015; Li et al. 2016). Other network topologies, including their advantages and disadvantages, can be found in the literature (Krimmling 2011; Olsen et al. 2014; REHAU AG 2015; Li et al. 2016). Since the evaluation of heating networks with rather low supply temperatures are in focus of this work, "twin-pipes" are used for modelling the pipes of the heating network. Twin-pipes are a co-insulated pair of media pipes with the same pipe dimension; the return and the supply line are inside the same insulation layer (Li et al. 2016). This type of pipe is particularly used in small local heating systems because they can be prefabricated which usually ensures a lower installation effort and costs (LOGSTOR 2015). In TRNSYS the twin-pipes are implemented using TYPE 313 (Dahm 2001; TRANSOLAR 2015b) and are parameterized according to (ISOPlus 2014; Li et al. 2016) (see also dimensioning of the pipes and pumps 4.6.3). Since the pipes are interacting with the soil the TYPE 313 (TRANSOLAR 2015b) is connected to TYPE 77 (TRANSOLAR 2015a). Depending on the used type of district heating pipes the recommended depth or cover height varies between 0.6….2.1 m (ISOPlus 2014; Rehau 2014). The boundary conditions assumed for the network modelled here can be found in Figure 4-8.



- Pipe depth in the ground (h): 0.6m
- Thermal conductivity pipe (λ_{ges}): 0.037 W/mK
- Thermal conductivity soil (λ_{soil}): 1.5 W/mK
- Distance between pipe centres (a): 0.0961m

Figure 4-8: Principle sketch of twin-pipes buried in the ground including parameters of the material (own sketch adapted according to (Rehau 2014; Li et al. 2016)).

The soil temperature is determined by simulation (TYPE 77) (TRANSOLAR 2015a). The supply and return of the thermal network is connected to the storage units (see chapter 4.7) via mixer (TYPE 649) (TRANSOLAR 2015a). For the purpose of the temperature control in the network, there is a bypass between the supply and return line, connected by tee-pieces (TYPE 11b, TYPE 11h) (TRANSOLAR 2015a).

4.6.2 Heating loop and piping for PWH supply inside the buildings

The pipes inside the thermal envelope of the buildings (heating loop and piping for PWH supply) are dimensioned according to German regulations (DIN V 18599-2: 2011-08; DIN V 18599-8: 2011-08). In contrast to the pipes of the heating grid, the hydraulic loops for SH and the pipes PWH are implemented in the building group model by using table values. The table values are generated with single-building simulations (TYPE 56 (TRNSYS 2005)) where only the hydraulic loops for SH and the pipes PWH are modelled by taking the user profiles (see chapter 4.3) and weather data (Meteotest 2015) into account. By this means the thermal inputs into the buildings of the building group model (internal gains caused by the thermal losses from the hydraulic loops) in resolution of 1 hour are taken into account in a simplified way. This procedure is advantageous because of the high accuracy of the values (or high achievable resolution of the data) and the simultaneous significant reduction of the computation time. Furthermore this approach corresponds to the goal of the doctoral thesis, the assessment of community energy supply systems, in the best way.

4.6.3 Dimensioning of the heating loops

As mentioned in section 4.6.1 a radial network equipped with twin-pipes is selected and established for LTDH supply (see Figure 4-9). In the heating centre (HC) storage units and energy suppliers are located. The buildings (e.g. A1, for definition see chapter 4.3) are connected by service pipes (SeP) which are linked by network nodes (NN)[9] to the supply pipes (SuP) (Olsen et al. 2014). For dimensioning of the pipes an optimum of investment and operating costs needs to be found. Large diameters for example lead to reduction of operation cost but the larger the diameter the larger the investment costs (Raab 2006).

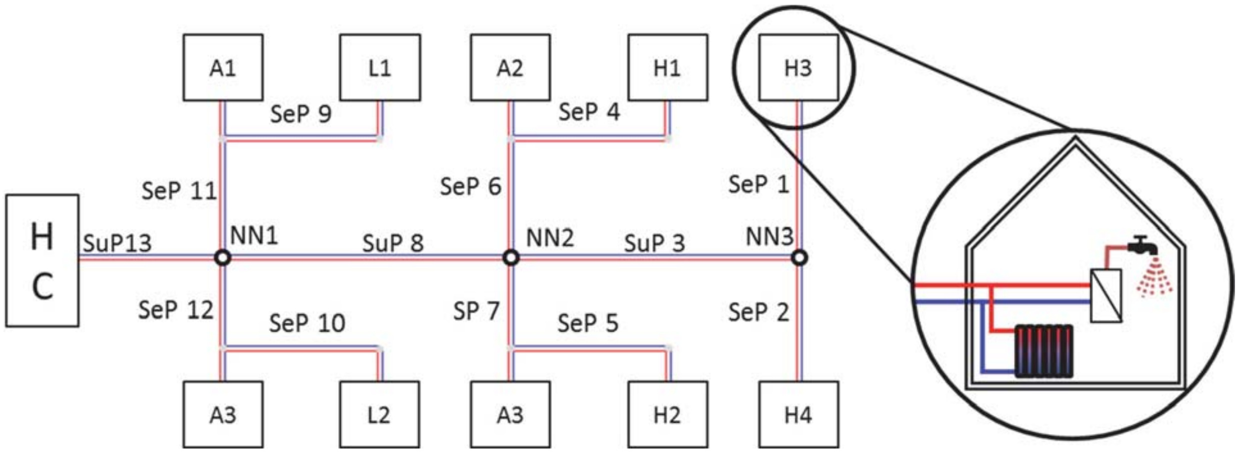


Figure 4-9: Description of the heat network including service pipes (SeP) and supply pipes (SuP), network nodes (NN) and schematic description of the building supply.

In order to determine the trench length calculation rules and data from (AGFW 2015) are used to derive a specific value for the installed meter per connection in the network. By specifying the number of consumers, a total trench length of 680 m is obtained for the network.

The network equipment (pipes and pumps) is dimensioned using the maximum mass flow. The maximum mass flow is a function of the required mass flows of the emission systems (see chapter 4.4) and the tapping profiles occurring in each service pipe (SeP) (see chapter 4.3). In order to calculate the total pressure loss, the diameter of each service and supply pipe has to be determined based on a directional speed which is not to be exceeded (Krimmling 2011; Glück 1988; Nussbaumer, Thalmann 2016; Olsen et al. 2014). According to (ISOPlus 2014) a maximum flow velocity w of 1 m/s[10] is assumed in this work. The inner pipe diameter d is determined by continuity equation (Herwig 2006):

$$\dot{V} = A \cdot w = \pi \cdot \frac{d^2}{4} \cdot w \qquad (4\text{-}13)$$

$$d = \sqrt{\frac{4 \cdot \dot{V}}{\pi \cdot w}} \qquad (4\text{-}14)$$

[9] As part of the modelling process the NN are reduced to a number of 3 instead of 5 in order to reduce the calculation time. Test simulation show that deviations are below 0.2 %, for this reason this simplification is considered to be permissible.

[10] At these speeds, the fluid is in the turbulent range. The fluid in the tube is mixed, which results in a good transport of the fluid.

The determined ideal inner pipe diameters are compared with the manufacturer data from (ISOPlus 2014; Rehau 2014). Based on this data a suitable diameter is selected. For the selected diameter, the flow velocity is calculated by equation (4-13):

$$w = \frac{4 \cdot \dot{V}}{\pi \cdot d^2} \tag{4-15}$$

With the obtained data, the total pressure loss of the network can be calculated. It results from the sum of the pipe friction losses, as well as the pressure losses caused by building equipment (Krimmling 2011; Wischhusen et al. 2005):

$$\Delta p_{ges} = \sum_i \Delta p_{pipe,i} + \sum_j \Delta p_{E,j} \tag{4-16}$$

The pipe friction losses are determined as follows (Krimmling 2011; Herwig 2006; Wischhusen et al. 2005):

$$\sum_i \Delta p_{pipe,i} = \sum_i \frac{\rho}{2} \cdot w^2 \cdot \left(\lambda \frac{l}{d}\right)_i \tag{4-17}$$

Here, the pipe friction coefficient λ is calculated using the Prandtl-Colebrook equation (Wischhusen et al. 2005):

$$\frac{1}{\sqrt{\lambda_1}} = -2 \cdot \lg\left(\frac{2{,}51}{Re\sqrt{\lambda_0}} + \frac{k}{3{,}71 \cdot d}\right) \tag{4-18}$$

The calculation is iterative; for λ_0 a starting value is estimated to determine λ_1. For the next iteration, the value for λ_1 determined in the preceding step is used for λ_0. This process is repeated until λ_1 no longer changes noticeably (Zanke 2013).

The Reynolds number correlates between inertial and toughness forces and provides information about the turbulence of flows (Wischhusen et al. 2005; Herwig 2006):

$$Re = \frac{\rho \cdot w \cdot d}{\eta} \tag{4-19}$$

The individual losses due to installations are calculated (Krimmling 2011; Wischhusen et al. 2005):

$$\sum_j \Delta p_{E,i} = \sum_j \frac{\rho}{2} \cdot w^2 \cdot \xi_j \tag{4-20}$$

The pressure loss coefficients ξ are taken from (Glück 1988).

The required power for pumps which are intended to compensate for the pressure loss is calculated as (4-21). The pump is dimensioned according to manufacturer's specifications (e.g. (WILO 2009)).

$$P_{pump} = \frac{\dot{V} \cdot \Delta p_{tot}}{\eta_{pump}} \tag{4-21}$$

The calculated pumping and piping parameters for the new buildings cluster is found in Table 4-7 and the parameters for the existing building cluster is found in Table 4-8.

Table 4-7: District heating pipes for new building clusters.

	Unit	SuP 13	SeP 12	SeP 11	SeP 10	SeP 9	SuP 8	SeP 7	SeP 6	SeP 5	SeP 4	SuP 3	SeP 2	SeP 1
Massflow	kg/s	3.81	0.39	0.35	0.29	0.24	2.53	0.39	0.35	0.45	0.46	0.88	0.53	0.35
Nominal diameter	DN	65	20	20	20	20	55	20	20	20	20	32	20	20
Velocity	m/s	0.72	0.68	0.96	0.8	0.66	0.67	0.67	0.96	0.78	0.8	0.87	0.91	0.96
Pressure	kPa	13.5	6.1	14.0	30.2	20.2	5.0	7.1	14.6	23.6	24.4	18.6	10.5	15.5

Table 4-8: District heating pipes for existing building clusters.

	Unit	SuP 13	SeP 12	SeP 11	SeP 10	SeP 9	SuP 8	SeP 7	SeP 6	SeP 5	SeP 4	SuP 3	SeP 2	SeP 1
Massflow	kg/s	3.37	0.34	0.45	0.45	0.45	1.78	0.34	0.3	0.34	0.34	0.55	0.3	0.2
Nominal diameter	DN	80	25	20	20	20	65	25	20	25	25	32	25	20
Velocity	m/s	0.56	0.80	0.80	0.94	0.92	0.92	0.80	0.92	0.78	0.76	0.76	0.56	0.80
Pressure	kPa	12.8	5.5	13.6	26.2	18.3	4.3	5.5	13.6	19.1	19.8	15.5	9.6	13.4

In addition to the distribution in the heating network the heat must also be distributed inside the buildings. As mentioned in chapter 4.6.2 the heating loops are simulated by using the single-building models. In the course of the dimension of the pipes it is assumed that heating water for space heating and PWH are provided in separate pipes, whereby the pressure losses are determined for the design of the respective pump capacity. The estimation of the pressure loss in the PWH pipes is carried out analogously to the method described above for the pressure loss determination of the heating network. In order to calculate the pressure loss of the pipes for SH, the following equation is used (WILO 2009) :

$$\Delta p_{Bui,Hz} = R_{pipe} \cdot L_{pipe} \cdot ZF \quad (4\text{-}22)$$

The pipe friction losses R_{pipe} are estimated to be 100 Pa/m and the factor $\mathbf{ZF}$ is estimated to be 2.6. The length of the pipes $\mathbf{L_{pipe}}$ are calculated according to building geometry (see chapter4.2) (Grundlagen der Pumpentechnik 2009; WILO 2009):

$$L_{pipe} = (L_{Bui} + B_{Bui} + H_{Bui}) \cdot 2 \quad (4\text{-}23)$$

The calculated pumping and piping parameters are found in Table 4-9.

Table 4-9: Overview of pressure losses and pinpng length inside the buildings.

	Units	A1	A3	L1	L2	A2	A3	H1	H2	H3	H4
$\mathbf{L_R}$	m	44.63	48.76	47.19	48.76	44.63	48.76	48.76	-	47.19	48.76
$\mathbf{\Delta p_{Bui.Hz}}$	Pa	11 605	12 678	12 269	12 678	11 605	12 678	12 678	45 500	12 269	12 678
$\mathbf{\Delta p_{Bui.DHW}}$	Pa	22 218	22 218	22 218	22 218	22 218	22 218	22 218	22 218	22 218	22 218
$\mathbf{P_{P.grid}}$	W_{el}	10.72	13.50	6.84	9.24	10.72	13.39	16.47	57.77	11.32	19.29
$\mathbf{P_{P.PWH.Bui}}$	W_{el}	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.70
$\mathbf{P_{P.Grid.Bui}}$	W_{el}	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.70

4.7 Thermal storages

Since the model comprises different types of energy supplying units (see chapter 4.8) a storage tank and a seasonal storage are implemented in the model. Both units are buried in the ground, hence heat losses are regarded as heat conduction to the soil.

The storage tanks (or buffer storage) are used in connection with the GSHP and the CHP. The storage device serves for buffering the peak loads which leads to a longer runtime of the energy suppliers and resulting to a higher level of annual use of the provided heat. The buffer storage is modelled by using Type 4c (TRANSOLAR 2015a) with five thermal layers. In accordance with (AGFW 2016a; Eicker 2012), the volume of the tank is assumed to be 20 m³ and the U-value of the insulation is considered to be 0.16 W/m²K (Bodman et al. 2005).

The seasonal storage (Type 342 – XST) (TRANSOLAR 2015c) is used in combination with a solar thermal collector field (ST arrays). As part of the model a hot-water heat storage (Schmidt et al. 2004) is used, since they are applicable regardless of the locations. The greatest advantage of a seasonal storage is the seasonal decoupling of heat supply and demand. The maximum temperature in a seasonal storage is 80…90 °C (Bodman et al. 2005). The thermal insulation and the size of the storage are designed according to (Marx et al. 2012; Schmidt et al. 2004; Bodmann et al. 2001). The layer thickness of the tank wall is 0.5 m, the thickness of the bottom is 0.35 m and the thickness of the cover is 0.65 m. A thermal conductivity of 0.1 W/m²K is assumed for the total insulation. With regard to the desired solar coverage, the aperture area of the solar thermal system and the storage size are adapted accordingly (Eicker 2012). The capacities of the seasonal storages are strongly dependent on the size of the collector field and the additional supply technology. The storage sizes for the respective case studies can be found in chapter 6. The insulation and the size of both the storage tank as well as the seasonal storage are verified by simulations.

Next to its application for load shifting, the storages act as an interface between the supply line of the LTDH-network and centralized energy supplying units. Depending on investigated supply scenario, the energy suppliers and the storage devices are interconnected (Figure 4-10).

By using the valves (1) and (2) the storages can be charged or re-charged respectively and activated or de-activated. If e.g. high solar yields are achieved, the seasonal storage is charged. As soon as the seasonal storage is recharged, HP and CHP can be activated to guarantee the uninterrupted heat supply. For the operation of the HP and CHP a small buffer storage is available. Depending on the selected supply scenario all supply units can be operated individually or in combination. All energy suppliers can be enabled or disabled, using the pumps and the valves (1) - (4). Additionally these pumps and valves (1) - (4) regulate the mass flows. As long as the temperature level in the seasonal storage is above the return temperature of the network (6), the residual heat can be used for reheating the buffer storage by activating valves (2) and (4). If the supply temperature is higher than the required supply temperature in the network, the bypass valves (5) and (6) are used to control the return flow.

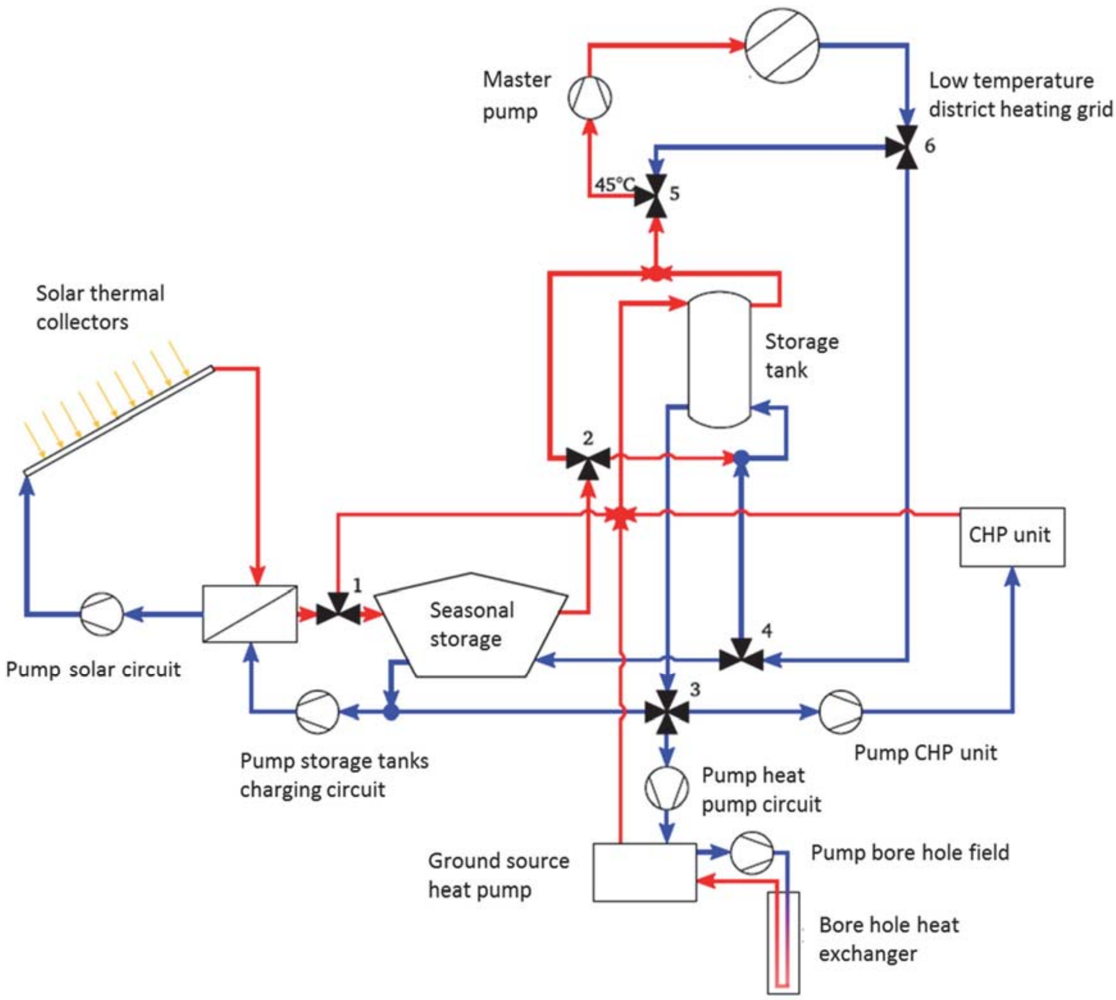


Figure 4-10: Principle sketch of the interconnections of the energy suppliers and the storage devices.

4.8 Energy suppliers

The focus of the simulation studies is on renewable energy based district heating supply. For that reason the utilization of near-surface geothermal energy by means of borehole heat exchangers (BHE), the use of solar energy and a bio-methane powered CHP are selected to be suitable energy sources. As part of the exergy assessment (see chapter 5) different decentralized and centralized supply concepts are compared. As decentralized comparative variants condensing boilers and decentralized heat pumps are selected.

4.8.1 Solar thermal collectors and solar district heating (SDH)

The main components of the solar thermal system which is connected to the LTDH is shown in Figure 4-11. The solar radiation is exploited by using a collector field which consists of flat plate collectors (TYPE 1b) (TRANSOLAR 2015a). The collector arrays are placed on the roof or close to the buildings. By using a heat exchanger (TYPE 5b) (TRANSOLAR 2015a), the solar circuit is connected to the storage circuit. The storage circuit comprises a seasonal storage (TYPE 342) (TRANSOLAR 2015b) and a storage tank (TYPE 342) (TRANSOLAR 2015c) as well as circulation pump (TYPE 114) (TRANSOLAR 2015c) and different valves (TYPE 647) (TRANSOLAR 2015a). The characteristics of the storage tanks are discussed in detail in section 4.7. In addition, a peak load boiler is implemented, which is directly connected to the storage tank. In some investigated scenarios (see case studies in chapter 6) the peak load boiler is replaced by other, renewable energy suppliers. By using a bypass at different stages of the model the required supply temperature can be achieved. The whole solar system is connected to the district heating system which is discussed as part of chapter 3.3.

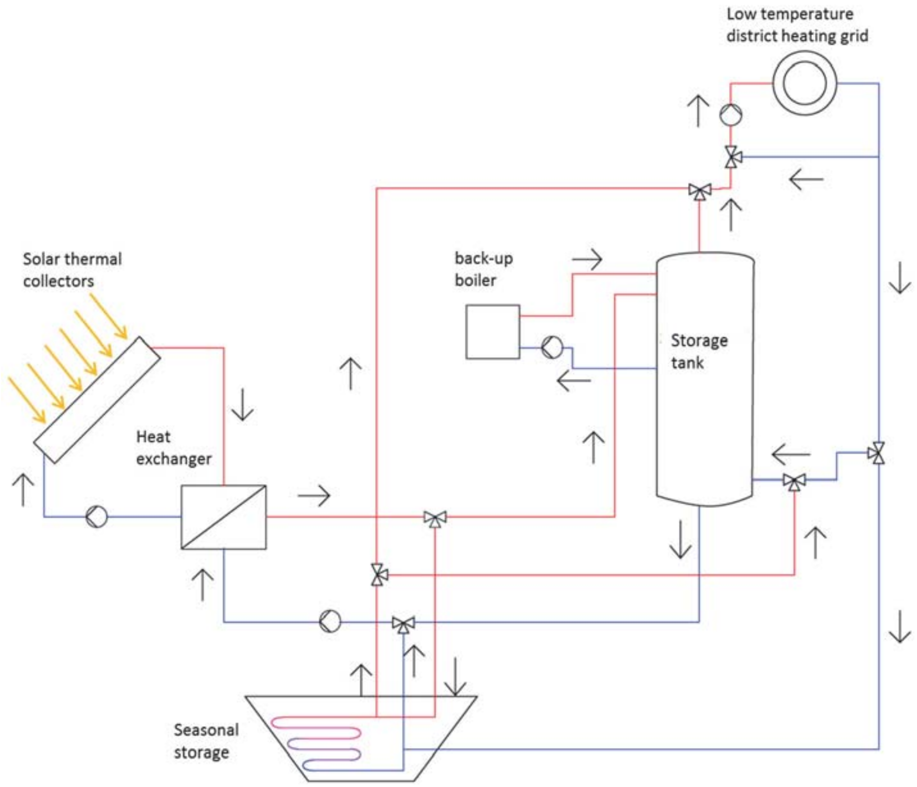


Figure 4-11: Principle sketch of solar thermal system (solar collector and storages) connected to low temperature local heating grid.

The characteristics of the flat plate collectors of (Winkler Solar 2014) were used for dimensioning of the solar thermal system. The specific mass flow through the collectors is assumed to be 15 l/m²s (Schmidt et al. 2004). The heat transfer medium used is a 33 % water-glycol mixture with a density of 1.04 kg/m³ and a specific heat capacity of 3,720 J/(kgK) (pro KÜHLSOLE 2014). The angle of incidence of the collectors has a significant influence on the solar yield. Some literature sources indicate angles of 30…60° for solar thermal collectors (Hilz 2010). Basically, the angle has to be chosen in a way that stagnation during summer or tank losses are avoided but a sufficient storage charge for covering the heat demand is ensured. By using (Meteotest 2015; TRNSYS17 2014) the optimum angle at Kassel site is determined in several test simulations. The simulations showed that the optimum angel is 39° at city of Kassel (Schneider 2015).

Solar district heating (SDH) offer energy, exergetic and economic (Heidemann et al. 2005) advantages in comparison to small plants. The performance of SDH is mainly dependent on solar fraction f_{sol} which indicates the proportion of the total energy demand that can be covered by the SDH system (Schabbach, Leibbrandt 2014):

$$f_{sol} = \frac{Q_{sol,use}}{Q_{use}} \tag{4-24}$$

It is well known that the highest level of radiation is available during the summer months but the required heating energy is required in the winter months. For shifting the load, a seasonal storage is required. Nevertheless, high solar coverage (solar fraction rates) lead to over dimensioning of the storages and the collector field. Therefore, the SDH system realized in Germany have solar fraction of 30…70 % (Quaschning 2015; Eicker 2012; Bodman et al. 2005).

The SDH system is controlled according to the principle shown in the schedule (Figure 4-12). The system is activated as soon as at least 150 W/m² of solar irradiation is available and at least a temperature rise of 7 K is to be expected. These values have proven to be suitable during several test simulations (Schneider 2015). In the summer months, the seasonal storage is thus exclusively charged. As soon as the temperature drops below the set-point temperature, the storage tank is charged. If the temperature in the buffer store rises rapidly in the spring months because of the solar gains, the load is again switched to the seasonal storage, while $T_{max, BS}$ > 62 °C has proven to be suitable. In this way also during winter time low heat gains are used.

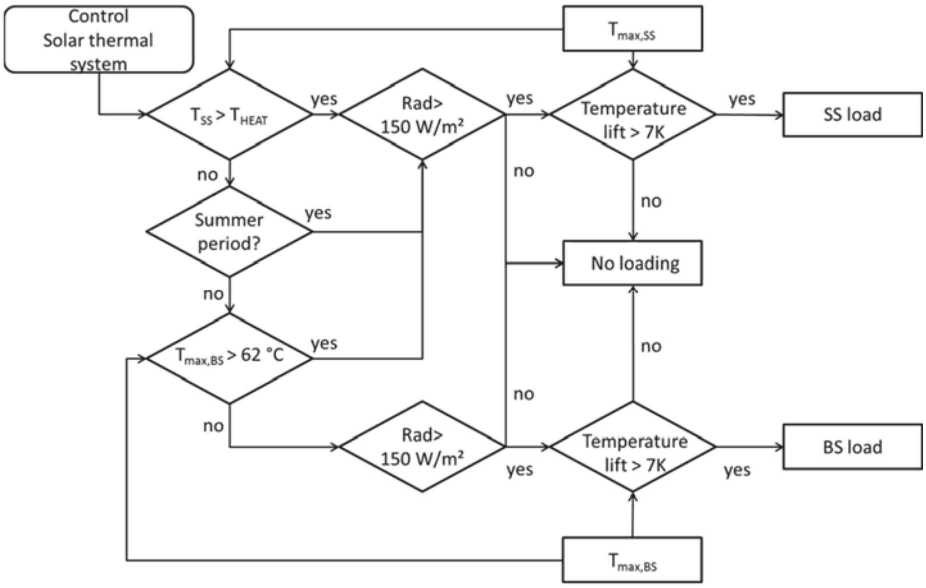


Figure 4-12: Flow chart for control solar thermal system.

The control strategy developed as part of this thesis is implemented in the model using the controlling unit (TYPE 15-2) (TRANSOLAR 2015a).

4.8.2 Ground Source Heat Pump (geothermal district heating)

The main structure of the geothermal system, which is connected to the LTDH, is shown in Figure 4-13.

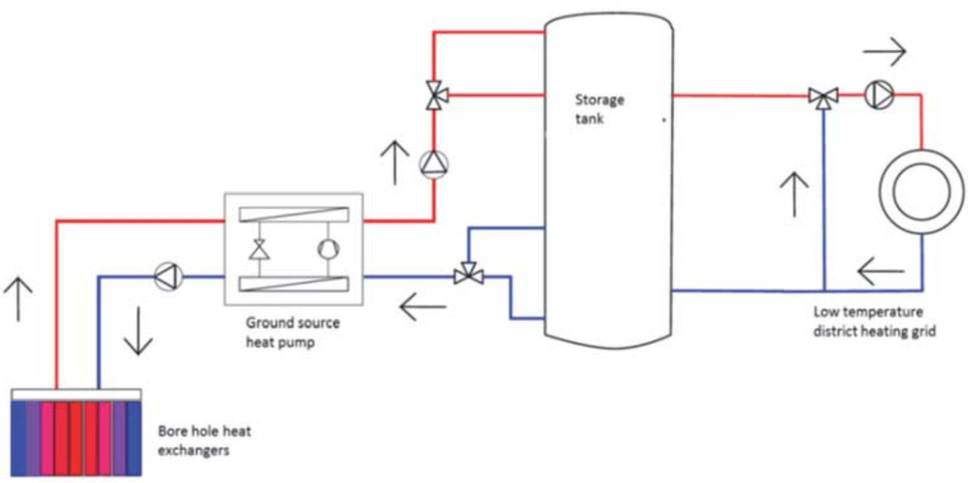


Figure 4-13: Principle sketch of heat pump system (borehole heat exchangers, ground sources heat pump and storage) connected to low temperature local heating grid.

As part of the model borehole heat exchangers (double-u geothermal probes), serve as a heat sources (TYPE 557) (TRANSOLAR 2015c) for the ground source heat pump (TYPE 668) (TRANSOLAR 2015a). The geothermal probes provide the required thermal capacity for evaporating the refrigerant in the heat pump (VDI 4640 2015). The ground source heat pump (GSHP) charges a storage tank, which is described as part of chapter 3.4. As part of this work the GSHP is also used in case of supply of single buildings (decentralised supply) without consideration of a LTDH grid which is regarded as part of chapter 6.1. For design of the thermal probes the evaporation capacity $\dot{Q}_{BHE}$ is determined according to (VDI 4640 2015):

$$\dot{Q}_{BHE} = \frac{\dot{Q}_{GSHP}}{COP} \cdot (COP - 1) \tag{4-25}$$

For calculation of the heat output of the GSHP and the evaporation capacity the coefficient of performance (COP) needs to be taken into account which is a performance indicator of the heat pump. The COP is comparable to the energy efficiency and describes the ratio of useful heating provided to work require (Quaschning 2015):

$$COP = \frac{\dot{Q}_{out}}{P} \tag{4-26}$$

The ratio of evaporation capacity and specific evaporation capacity allows the calculation of the total length of the borehole heat exchanger l_{BHE} (Quaschning 2015).

$$l_{BHE} = \frac{\dot{Q}_{BHE}}{\dot{q}_{BHE}} \tag{4-27}$$

Due to licensing requirements, a depth of borehole heat exchangers (BHE) greater than 100 m is not common in the household sector (Hou 2013; Glück 1988). As a result, the maximum probe depth is set to 100 m. The number as well as the depth of the probes varies depending on the variants studied (see chapter 6). The probes and the pump are dimensioned using the software tool "EWSDruck" (Huber, Ochs 2007). As refrigerant in the geothermal system a 25 % water-glycol mixture with a density of 1053 kg/m^3 and a specific heat capacity of 3800 K/(kgK) is used (pro KÜHLSOLE 2014). The temperature difference within the probe is assumed to be 5 K (VDI 4640 2015; Glück 1988). The ground source heat pump (GSHP) is designed using the standard heat load (see chapter 4.2) and the “95%-quantile” (see chapter 4.2).

In the course of modeling, the selection of suitable water / brine heat pumps must be carried out in order to cover different temperature levels and different performance ranges. In the individual scenarios, different temperature levels are taken into account for the existing and new buildings, in order to guarantee heat coverage. Furthermore, a variation of the temperature is carried out for selected scenarios. In addition, a combination of different energy suppliers, which have in particular effects on the performance range, has been achieved. The heat pumps are simulated using characteristic curves. The heat pumps “Vitocal 300/350-G BW 301.A.45 (P_{th} = 45 kW) (Viessmann Deutschland GmbH), WPS 60 (P_{th} = 60 kW) (Bosch Thermotechnik GmbH (Buderus) 2014) and “Vitocal 350-G BW 352.A132/ BW 352.A132SA” (P_{th}=114 kW) (Viessmann Deutschland GmbH 2015b)[11] are applied in the simulations for the centralised scenarios. As part of the decentralised scenarios, the GSHP “Vitocal 350-G Typ BW 351.A07, BWS 351.A07” (P_{th} = 60 kW) are used (Viessmann Deutschland GmbH 2012).

[11] It has to be noted critically that the HP is only available up to a temperature of 73 °C, the difference of 2 K was determined by interpolation.

By taking economic aspects and the "LowEx approach" into account, the control of the heat pump is designed in such way that too frequent clocking (activation or deactivation) of the GSHP is avoided (Figure 4-14).

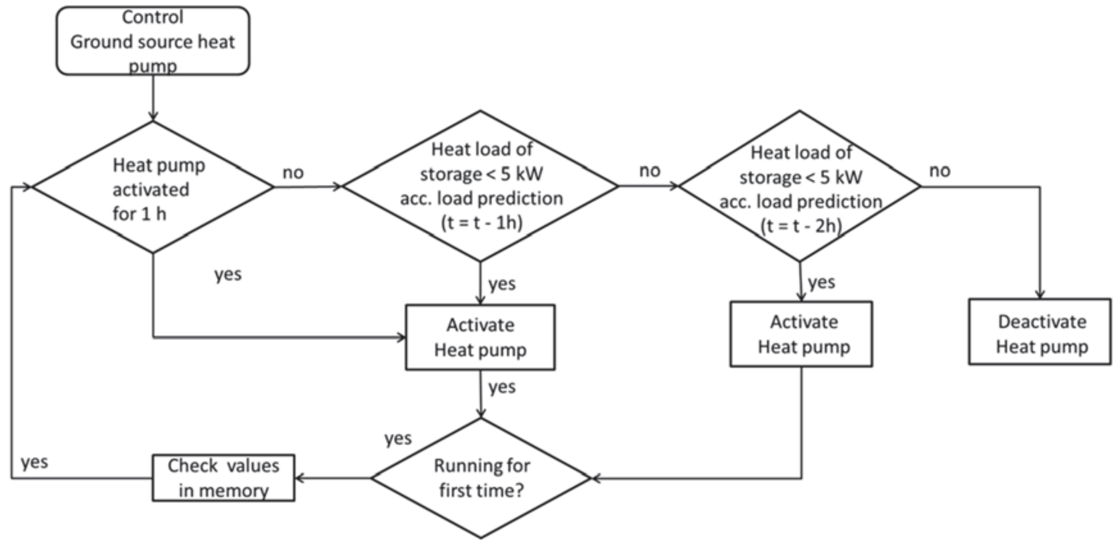


Figure 4-14: Schedule of the control strategy developed for heat pump and CHP units.

For realisation of the control strategy a standard controlling unit of TRNSYS (TYPE 2b) (TRANSOLAR 2015a) was modified in such way, that the target of control is achieved. It is determined, that after each starting process the GSHP is at least two hours in operation and after each deactivation the heap pump will not reactivated for at least 2 hours (Wegesin 2011). However, security of supply has to be guaranteed at the same time. Therefore it was determined that the heat output of the tank should not drop below 5 kW, so that drinking water supply is guaranteed at all times. An important control parameter here is the weather prediction from which a load prediction can be determined for a certain period. In several test simulations it was verified, that the developed control strategy can be applied to both new buildings and existing buildings (Blaese 2016; Rösel 2015).

4.8.3 Combined Heat and Power (CHP) plant

The main structure of the CHP plant, which is connected to the LTDH, is shown in Figure 4-15.

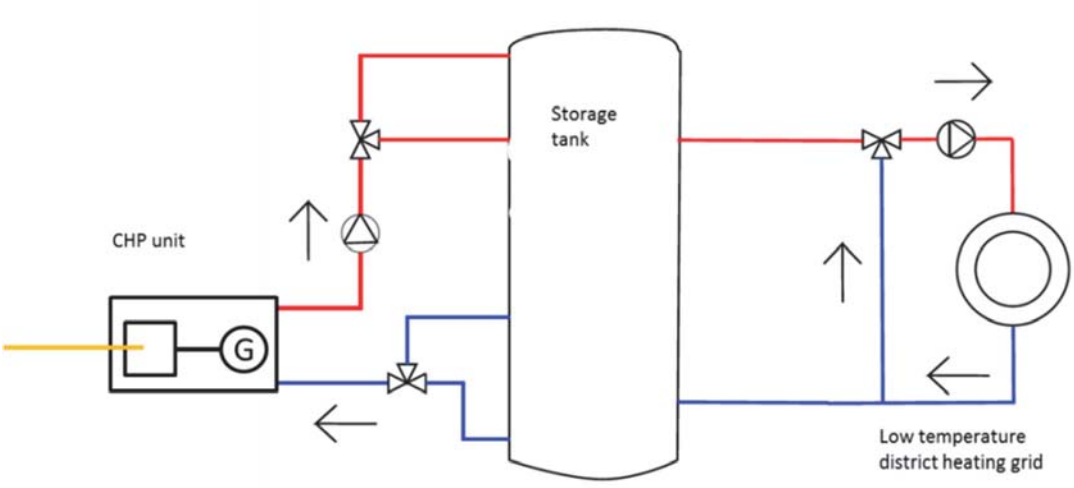


Figure 4-15: Principle sketch of CHP system (CHP unit and storage) connected to district heating grid.

Due to the target of this work a heat-driven CHP is selected. The produced electricity is therefore only regarded as a by-product, although it is actually the higher-quality product. As a rule, CHP are not used as the sole heat generator but only to cover the thermal base load. In this way, the full load hours are maximized, which in turn has a positive effect on profitability through the sale or consumption of electricity.

The dimensioning of the CHP is carried out in the same way as the GSHP (see chapter 4.8.2). At the cogeneration plant, natural gas is used. For modelling TYPE 152, is used which is based on data of a micro-CHP (Senertec Dachs HKA G 5.5) (I. Beausoleil-Morrison and U. Arndt 2007). Due to the targets of the simulation studies, an efficiency of η_{el} = 0,35 und η_{th} = 0,55 according to (ASUE 2011) is implemented. The CHP also benefits from long running times (Stein 2006) and is therefore operated with the same control strategy as the GSHP.

4.8.4 Condensing boilers

As part of the thesis and in accordance with (Maßong 2014), boilers are regarded as reference technologies and are not used as a central unit but decentralised in each individual building. Condensing boilers burn light fuel oil resp. gas and additionally use the latent heat of the water vapour in the exhaust gas by condensation. The condensing boilers are designed according to standard heat load (see chapter 4.2) with an additional charge for potable water hot. For the implementation in TRNSYS a new model without the heating grid was applied where TYPE 700 is used for the boiler.

5 Exergy-based assessment of community supply

Exergy indicates how well the working potential of resources is being used (Schmidt et al. 2016b). This insight cannot be retrieved solely with energy analysis. The exergy concept can be linked with economic and ecological parameters but does not inherently include other objectives such as maximizing the use of renewables or minimizing emissions or costs (Jansen, Meggers 2016; Kallert et al. 2016). For that reason additional technological and planning evaluation parameters are identified and added to the exergy-based analysis developed in this thesis. For the evaluation the following parameters are used: energy and exergy efficiency, CO_2 emissions (environmental impacts), full costs (economic analysis), space requirement (e.g. solar collector arrays, borehole field, local heating/ gas grid) and future technological development (future electricity mix of fluctuating renewable energy suppliers). The different factors are used for evaluation of different components of the energy systems (e.g. energy suppliers). For comparison and evaluation the different evaluation factors are classified by Hard Evaluation Factors (HEF) and Soft Evaluation Factors (SEF) (Figure 5-1). The difference between the classifications factors[12] is the approach as they were determined for the analysis carried out in chapter 7. HEF are determined based on different calculation rules respectively standards and SEF are estimated on an approximate basis.

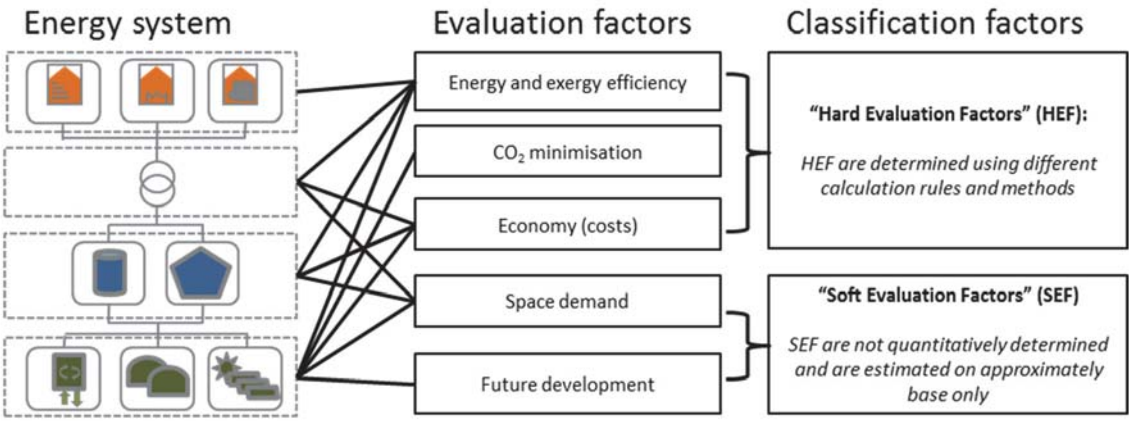


Figure 5-1: Main principle of the assessment using the exergy-assessment approach.

Since the focus is on technical comparison of several predefined systems (chapter 6) and not on the optimisation of single components of the energy system, the evaluation parameters are not linked to the steps of the energy conversion chain and are thus regarded independently. Furthermore the advantage of the exergetic assessment for district heat supply is to be demonstrated in this thesis (see also chapter 1.2). The potential of the exergetic analysis can be comprehensively examined only independently from other parameters. For that reason no direct correlation between the different evaluation factors is made respectively analysed in the thesis' work. As a result the different evaluation factors represent independent evaluation criteria applied in the technology comparison.

[12] A possible alternative to this approach would be the consideration of the size of the supply area, e.g. as "extensive" or "intensive" assessment variables (based on the thermodynamic function of state (Baehr, Kabelac 2012)) respectively classification factor. Thus, extensive assessment variables would be dependent and intensive assessment variables would be independent on the size of the supply area. However, this approach will not be discussed further.

However it should be noted that in the literature several approaches can be found, which are combining e.g. cost or sustainability and exergy assessment. One possibility to extend the energetic and exergetic evaluations to include economic and environmental and climate-relevant aspects are exergo-economic and exergoecological methods. In these methods, cost factors are normally expressed by multiplication (e.g. (Schlagermann 2014; Riedl 2007)). In this way, process steps are monetarily quantified and thus improvement potentials are clearly illustrated.

5.1 Energy and exergy efficiency

As part of chapters 2 and 3 a very detailed method for exergy assessment of renewable-based low temperature district heating supply is introduced, which provides the main basis for the exergy assessment in chapter 7.1. Since in this chapter, however, a comparison of energy and exergy assessment is carried out, appropriate evaluation parameters are selected based on an extensive literature review. The literature research shows that a number of different benchmarking parameters for assessment of energy conversion processes are existing (e.g. (Torio, Schmidt 2011; Bargel 2010)). In the course of a preliminary study it was found that the overall energy and exergy efficiency are the most suitable evaluation parameters and meet the criteria for comparative evaluation in the best way.

In case of energy assessment as most common benchmarking parameter for evaluating energy systems the energy conversion efficiency η is applied. As part of the heating systems considered, the energy efficiency η is composed of the effort (total, primary energy used) and the use (heat demand and PWH demand of the ten buildings).

$$\eta_{sys} = \frac{E_{Output}}{E_{Input}} \tag{5-1}$$

In order to assess the quality aspects the overall exergy efficiency ψ is used. Different expressions and definitions of this parameter can be found in literature (e.g. (Szargut 2005; Torío et al. 2009; Bargel 2010; Riedl 2007; Fratzscher et al. 2013; Jentsch 2010; Schmidt 2012a)). According to the approach of (Fratzscher et al. 2013), the consumed exergy is divided into internal and external losses (see equation (5-2)). External exergy losses are calculated similar to energetic losses, which leave the system without producing work (Ex_{loss}). Internal exergy losses are also described as exergy destruction (Ex_{dest}), and can be regarded as the systems internal loss of work potential (Bargel 2010). Only by considering these overall losses, the qualities or the ability of transformation (Jentsch 2010) are taken into account. If the quantification of the exergy destruction is done, the potential for improvement can be identified. For assessing the exergy destruction occurring as part of the energy conversion chain of the energy system, the method presented as part of chapter 3 is applied.

$$\psi = \frac{Ex_{in,env}}{Ex_{in,r}} = \frac{Ex_{in,r} - \overbrace{Ex_{loss} - Ex_{destr}}^{\text{Consumed exergy}}}{Ex_{in,r}} \tag{5-2}$$

Depending on whether the exergy efficiency is referred to a single component or a process of a whole energy system, or to all processes and components integrating the system, so-called "single" (see equation (5-3)) and "overall" (see equation (5-4)) exergy efficiencies can be defined (Torío 2012).

$$\psi_{single,r} = \frac{Ex_{in,env}}{Ex_{in,r}} \tag{5-3}$$

$$\psi_{overall} = \frac{Ex_{in,env}}{Ex_{in,prim}} \tag{5-4}$$

The overall exergy efficiency which is derived from the product of the single efficiencies of the single processes is used in this work. The application of this exergy efficiency allows characterising the total performance of a complete energy system. Overall exergy efficiencies of different energy systems (e.g. different supply scenarios for a building group) can be directly compared to each other, since the same reference temperature is used for the exergy analysis of all supply systems.

5.2 Evaluation of GHG emissions

By the year 2030 all countries of the European Union have committed themselves to reduce their GHG emissions by at least 40 % compared to the year 1990 for climate protection. This has to be achieved mainly through the promotion of renewable energy and energy efficiency (BMWI 2016a).

The amount of emitted greenhouse gases (GHG) gives information about the climate efficiency, which is expressed as CO_2 equivalents (CDE[13]). CDE are used to determine the amount of natural gas, fuel oil and electricity supplied to the system. For this purpose the values listed in Table 5-1 are used, which are multiplied by the amount of the final energy demand calculated as part of the simulations in chapter 7.

Table 5-1: CO_2 equivalents (CDE) of the investigated energy carriers (GEMIS 2016; Fritsche, Greß 2016).

	Unit	CO_2 equivalents (CDE)
Natural gas	kg_{CO2}/kWh	0.250
Fuel oil	kg_{CO2}/kWh	0.320
Electricity	kg_{CO2}/kWh	0.535
Electricity (2030)	kg_{CO2}/kWh	0.374

5.3 Evaluation of costs (economic analysis)

In the course of the economic analysis the centralised as well as the decentralised supply variants (chapter 6) are evaluated by performing a total cost comparison. Since this thesis is focussing on generic case studies and not on an implementation project or a feasibility study, the assumptions made in this chapter are to be interpreted as an indication (reference values). The evaluation includes the supply units, the storage facilities, the thermal network respectively the gas network, as well as the substations. Any construction costs or renovation costs of the building are excluded from the examination.

5.3.1 General assumptions

The economic comparison of the individual variants is based on (VDI 2067 2012). In accordance to this this guideline, the costs are split into €/a according to capital related costs (investment), consumption related costs (fuel costs and costs for auxiliary energy) and operating costs (maintenance and repair). Furthermore miscellaneous costs (insurance, taxes and administration)

[13] It should be noted that the selection of the emission factors has a significant impact on the assessment of the energy suppliers. A description and discussion of other factors can for example be found in (Hertle et al. 2014).

and proceeds are regarded. To maximize synergies, the simultaneous embedding of the heating as well as the gas and the electricity grid into a common trench is assumed for the central variants. For the building stock only the renewal of the heat supply systems is assumed. Based on this assumption no residual values are credited.

Since the work is aimed at technology comparison of very small energy systems, incentives and funding (i.e. low-interest KfW loans) or any subsidies are considered to a very limited extent (see chapter 5.3.3). However, it should be noted, that these subsidies can have a significant influence on profitability, which provides the main basis for realisation of a refurbishment or new construction project by local authorities.

Global data, used in all variants, are found in Table 5-2 and Table 5-3. As part of all investigations net costs are regarded, which means that value-added tax (VAT) is not taken into account.

Table 5-2: Global data for analysis (VDI 2067 2012; Krenzin, Ebert 2011)

Observation period	a	20
Calculatory interest rate	%	5
Inflation rate	%	2
Staff costs	€/h	30

Table 5-3: Cost-relevant data of the investigated supplying units (VDI 2067 2012; Mangold et al. 2012; Stroh 2013).

	Service life (T_N)	Annual repairs (f_{Inst})	Annual maintenance and inspection (f_{W+Inst})	Effort for operation
	a	% of Invest.	% of Invest.	h/a
Solar thermal energy	20	0.5	1	5
Heat pump	20	1	1.5	5
Heat source systems	50	2	1	0
CHP	15	6	2	100
Condensing boiler	18	1.5	1.5	100[14]
Peak load boiler	18	2	1.5	
Chimney	50	1	2	0
Storage tank	20	1	1	0
Seasonal Storage	30	1	0.25	0
Heating grid	30	0	0.5	0
Gas grid	40	0	0.5	0
Substation	30	2	1	0
Pumps	18	2	1	0

To estimate the future development of the prices of the energy sources, data from (DESTATIS 2015) (consumer price index[15], basis year 2010) are set off against data from German Federal Ministry for Economic Affairs and Energy (BMWi) (BMWI 2016d). The evaluation shows, that the average annual inflation for all energy carriers increased by about 4 % between the years 2000 and 2015, wherein electricity has the highest rate and the heating oil the lowest rate of increase. However, it is also shown that the increase of prices has been lower in the last five years, excluding electricity. Since also further literature sources (e.g. (Oeko-Institut 2016; Leipziger Institut für Energie (IE

[14] The value 100 results from the presence of 10 boilers, it is assumed that one boiler requires 10 h/a for operation.
[15] Consumer prices for the investigated energy carriers include: work price for household-specific quantities, basic charges and VAT.

Leipzig) 2012)) assume a lower long-term increase, a lower inflation rate is considered as a part of the thesis. As simplification it is assumed that the price increase for electricity for households and heat pumps is very similar. The evaluation of the sources mentioned above showed that the price for heat pump or commercial electricity is not listed. For that reason the prices were requested at the ESCO of Kassel (Stadtwerke Kassel 2016). It turned out that the commercial electricity tariff for the expected electricity demand is partly equal to or higher than discounted heat pump tariffs.

Table 5-4: Overview of prices and price increases of different energy carriers (DESTATIS 2015; BMWI 2016b; Stadtwerke Kassel 2016; AGFW 2016b).

	Costs	Rate of inflation (last 15 a)	Rate of inflation (future)
	ct/kWh	%	%
Electricity (households)	29.24	4.80	3
Electricity (heat pump)	20.93	-	3
Natural gas	7.04	4.21	3
Fuel oil EL	6.05	4.07	3
District heating	8.87	4.26	3

As part of the considered cases, proceeds are generated through the generation of electricity of the CHP. A rate of inflation of 1 % is assumed for the proceeds from the sale of the CHP electricity (Graichen et al. 2016).

Table 5-5: Proceeds by CHP (BMWI 2016b; Graichen et al. 2016; co2online 2016).

	Unit	< 50 kW_{el}	50…100 kW_{el}
Internal consumption			
Work price of electricity	ct/kWh_{el}	22.27	22.27
+ Surcharge	ct/kWh_{el}	4.00	3.00
Σ Internal consumption	ct/kWh_{el}	26.77	25.77
Feed-in			
Power charge from network operator	ct/kWh_{el}	3.30	3.30
+ Surcharge	ct/kWh_{el}	8.00	6.00
+ Avoided network costs	ct/kWh_{el}	0.50	0.50
Σ Feed-in	ct/kWh_{el}	11.8	9.8

5.3.2 Overview of investment costs

The investment costs for the heating network consists of the cost of heating network (Table 5-6) and the substations (including pumps and storages). The data "greenfield locations" is used for the assessment of the new building clusters and the "infrastructure available" data is used for the existing cluster.

Table 5-6: Investment costs of heating network (Nussbaumer, Thalmann 2016) .

Nominal Pipe Size	Costs piping	Cost of earthworks		Total costs	
		Greenfield locations	Infrastructure available	Greenfield locations	Infrastructure available
DN	€/m	€/m	€/m	€/m	€/m
20	226	83	165	309	391
25	231	83	165	314	396
32	257	83	165	340	422
40	272	83	165	355	437
50	293	107	202	400	495
65	335	107	202	442	537
80	376	124	240	500	616

The investment costs for the gas grid are estimated to be 75 €/m in a simplified model according to (Stroh 2017). In contrast to the trench length of the heating network, the trench length of the gas grid differs for centralised and decentralised variants. The costs of the substations, 90 €/kW, are calculated according to a study by the Federal Ministry of Transport, Building and Urban Development (BMVBS) (BMVBS 2012). The price for the pump is assumed to be 500 €, based on a study of the Energy Efficiency Association for heating, cooling and CHP (AGFW) (AGFW 2016a).

For the buffer storage, the indicated costs of the Agency for Renewable Resources (FNR) (Hartmann et al. 2010) are used, which are based on a survey of manufacturers. Since the data was mainly collected for larger storage volumes, the costs for small storage volumes were determined by means of a correlation (Figure 5-2).

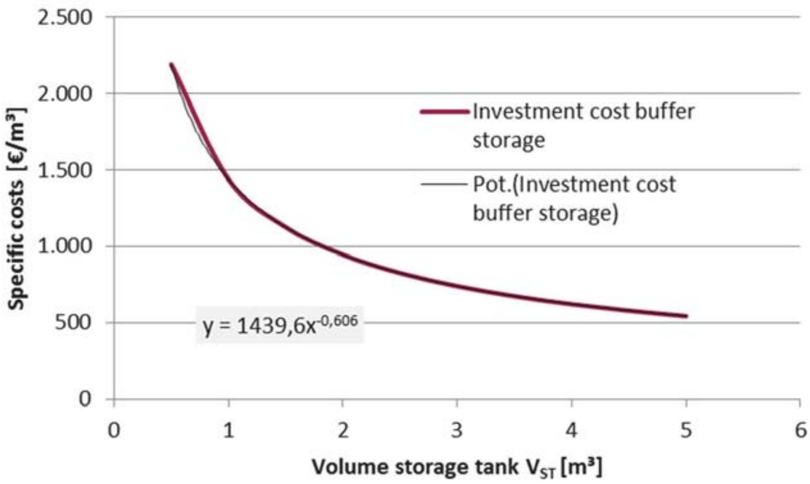


Figure 5-2: Specific investment costs and regression function storage tanks in accordance to (Hartmann et al. 2010).

The costs for the seasonal storage are taken from a study carried out by the Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems (solites) (Mangold et al. 2012), where the specific costs of various seasonal stores were analysed. Since the values spread widely, solites does not recommend a cost function but a band value. To create a function from this band, support points (fulcrums) were selected, which were located in the middle of the band (Figure 5-3).

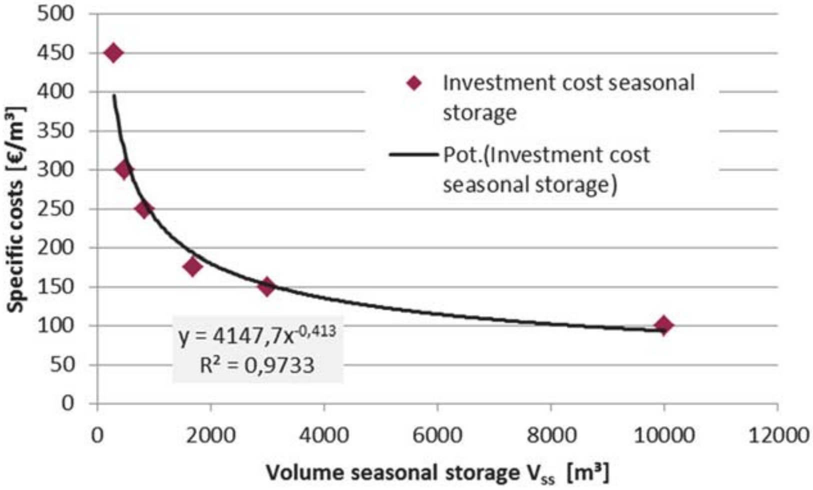


Figure 5-3: Specific investment costs and regression function of seasonal storage in accordance to (Mangold et al. 2012).

The costs for the heat pump are taken from a comprehensive study of (BMVBS 2012), which deals with the analysis of data for a reversible brine-water heat pump (COP > 4). The costs include all plant parts (e.g. earth probes) required for operation as well as transport, assembly and commissioning. Since the power required is not close enough to the performance of the heat pumps investigated in this work, a regression function was obtained from the data. For the heat source system, costs indicated by the German Heat Pump Association (BWP) are used. Here it is assumed that the total cost is 60 €/m (based on meters of drilling) (BWP 2016). This value is equal to the assumptions made in (Kaltschmitt et al. 2014).

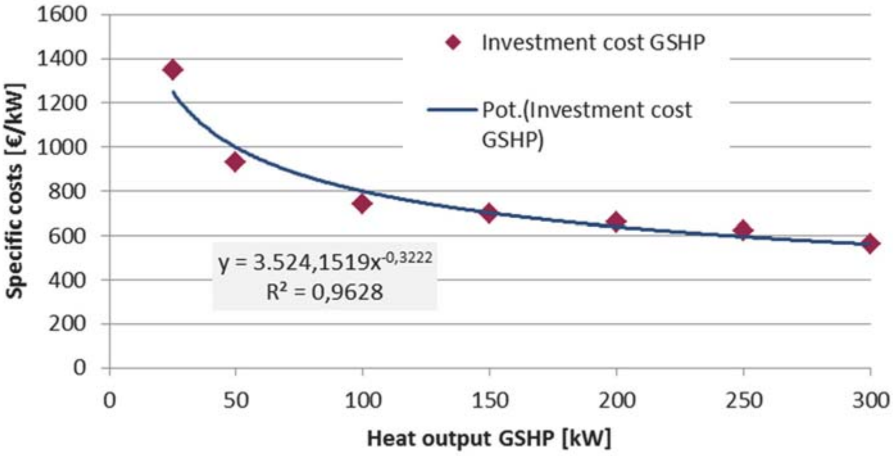


Figure 5-4: Specific investment cost and regression function for heat pump in accordance to (BMVBS 2012).

For combined heat and power (CHP) plants, two cost functions of ASUE (ASUE 2011) are used for the performance classes 30…157 kW_{el} and >157 kW_{el}. The data corresponds to the data indicated by (BMWI 2016b). Since the present functions are related to the electrical power, they were converted to the heating power by the electrical and thermal efficiency. The costs include all plant components required for operation as well as transport, assembly and commissioning.

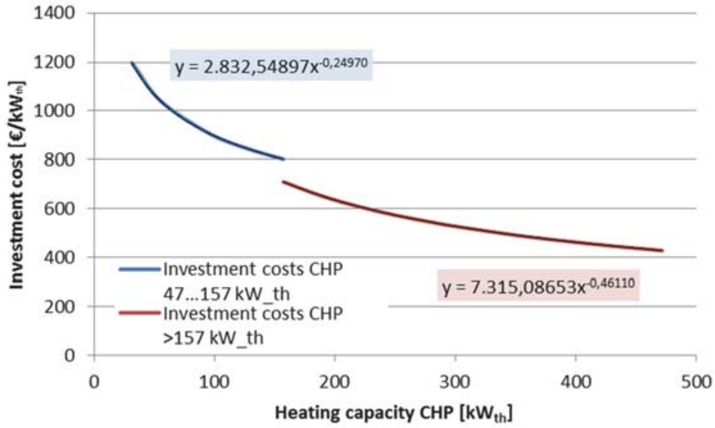


Figure 5-5: Specific investment costs and regression function for CHP in accordance to (ASUE 2011).

The costs for the solar thermal collector field are based on a study by BINE (Schnauss 2008), where large plant dimensions are considered. Since the data were mainly collected for collector areas up to 100 m², the costs for greater areas were determined by means of a correlation. The result of the correlation is validated by data of Department of Solar and Plant Engineering of the University of Kassel (Universität Kassel ITE (F. Pag) 2016) and additionally coincide with (Tjaden 2016).

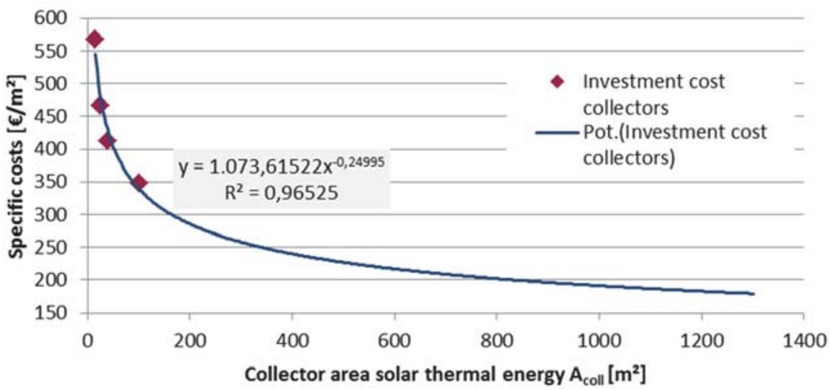


Figure 5-6: Specific investment costs and regression function for solar thermal energy in accordance to (Schnauss 2008).

The cost function for the condensing boiler is derived from a study by (Hartmann et al. 2010) and (BMVBS 2012), in which a cost function was determined by a market survey for devices <50 kW_{th}.

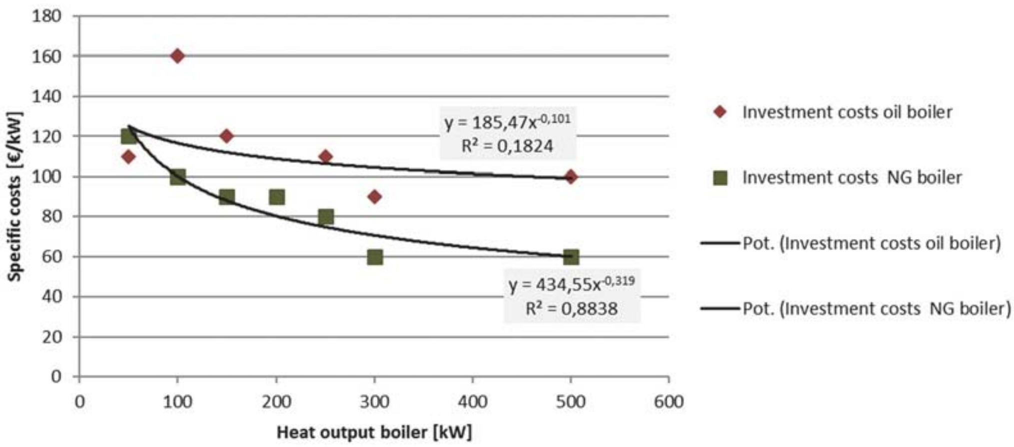


Figure 5-7: Specific investment cost and regression function for oil boiler and NG boiler in accordance to (Hartmann et al. 2010) and (BMVBS 2012).

In addition to the costs for the oil boiler, it is assumed that a tank with a volume of 3000 l is installed for the storage of heating oil. The cost function for the storage is taken from the TFZ (Hartmann et al. 2010). The costs are assumed to be 1958 € per building. Furthermore, a chimney has to be installed. The costs including installation are generally included at a rate of 2000 € per boiler (AGFW 2016a). The resulting costs of the total building equipment are consistent with other studies, e.g. from (Krenzin, Ebert 2011).

5.3.3 Programs to promote innovation

Subsidies can be included in the economic analysis only to a limited extent due to the small plant sizes installed in the area. Considered subsidies are summarized in Table 5-7. In the case considered, subsidies from the Federal Office for Economic Affairs and Export Control (BAFA), the Kreditanstalt für Wiederaufbau (KfW) and the combined heat and power law (KWKG) are eligible. In addition federal and municipal subsidies are not taken into account in the calculations.

Table 5-7: Subsidies for solar thermal, heat pump and CHP in Germany (Blaese 2016).

	BAFA	KfW	KWKG
Solar thermal energy	Only up to 100 $m^2_{Kollektor}$	> 30 $m^2_{collector}$ and heating grid: 40% of the investment sum	-
Heat pumps	< 100 kW_{th}: 100 €/kW_{th}	> 100 kW_{th}: 80 €/kW_{th}	-
CHP	Only micro CHP< 20 kW_{el}	Only for CHP using renewable resources	Proceeds (see 5.3.1)
Heating grid	-	60 €/m_{Trench}	CHP network with average pipe diameter < DN100: 100 €/m_{Trench}; max. 30% of the investment sum
Seasonal store	-	250 €/$m^3_{volume\ storage}$	CHP heat storage with > 50 m³: 250 €/m³; max. 30 % of the investment sum

5.4 Soft Evaluation Factors (SEF)

The SEF used in this work are not quantitatively determined and are highly dependent on the location as well as the size of the investigated area. In the course of this thesis, only indicative values are discussed, for that reason the factor considered here is a so-called "soft" evaluation factor (SEF).

5.4.1 Demand of space (weighted area units)

When considering an individual building respectively decentralised supply, the components of the supply system are generally located within the building envelope, which usually also represents the boundary for calculations. When evaluating building clusters (centralised supply), the consideration of the area utilization or area requirements of the individual supply components takes a comparatively high priority. This is of high relevance, particularly in the case of locally very limited supply areas, since locally available resources at the site (e.g. heat from geothermal probes) are directly connected with the overall system "building cluster".

The approach applied in this work is not aiming at replacing an exact planning process. In addition, this approach leaves questions unanswered regarding, e.g. the district heating connection rate or the import and export of fuels[16]. Therefore, the individual quantified space requirements are to be

[16] This also includes locally available or not-locally available resources.

understood as the mere space requirement, which has to be provided for the supply systems, whether it is installed on top of the buildings, within the buildings or in the supply area.

Since some areas become available for an almost unrestricted further use after the installation of the system components is completed (e.g. geothermal probes), other areas might only be useable with certain restrictions (accessibility for maintenance, e.g. thermal grid) and some will not be useable otherwise at all (e.g. ground-installed ST-collectors, seasonal storage), weighting factors are introduced. Those factors are expressed as a percentage. For example, a weighting factor of 100 % means that the area is not (and will not become) usable for other purposes at all, a weighting factor of 20 % represents an area, which can be used for other purposes with only negligible restrictions and an area with 0 % is usable without any restrictions after the initial installation work is completed. In order to counteract misleading conclusions, the estimated areas using weighting factors are converted into so-called dimensionless "surface units" as they do not reflect actual plant sizes.

The following assumptions are based on the assessment of the expected area requirements:

- **Heating centre:** The heating centre includes the generator units GSHP, peak load boiler and the CHP, which includes the control and the hydraulic equipment (e.g. pumps).
- **Storage units:** The storage units comprise the seasonal storage or the buffer storage, which are buried in the ground. When quantifying the required installation area, a simplified conversion of the storage volume to the area is made. In addition, the area of a circular ring, which is placed around the storage, is taken into account with a defined ring width for bulk or insulation material. The width of the circular ring is estimated with three meters for a seasonal store and with one meter for a storage tank.

The area of both heating centre and ground-installed storage devices are regarded as 100 % (since it cannot be used otherwise).

- **Heating or gas network:** The total length of the grid as well as the trench widths of one meter are taken into account to determine the required area for the gas or local heating network. As simplification it is assumed that a possible gas network requires a similar installation area as the local heating network. This simplification is permissible against the background of the solely calculation of the space requirements, since in no cases is the simultaneous laying of the gas and heating network is regarded. The area of heating or gas network is regarded to be 80 %, since the space is available for e.g. roads but has to be accessible for maintenance or repairs, i.e. it is usually not common to build permanent structures on the overlying surface.
- **Solar thermal collectors:** Solar thermal collectors can be installed on the roof of a building but also as a solar field on the ground. Areas of solar installations which can be accommodated on roof surfaces of the buildings are considered to be only 20 % of their utilized area in the evaluation. The area of ground-installed solar thermal collectors is regarded as 100 % (since it cannot be used otherwise).
- **Borehole fields:** Geothermal probes can interfere with each other if the distance between them is too small. According to (VDI 4640 2015), a minimum distance of 6 m is assumed for neighbouring probes in order to avoid negative influences. A strip of 3 m is taken into account around the earth probe field. For the geothermal probes it is assumed that 60 %

of the surface requirements are included in the assessment since the area becomes available for further utilization after the installation work is done. Possible uses: playgrounds, parking areas, recreation areas etc.

The NG boilers that are implemented as decentralised reference technology in the new building clusters are weighted with 0 %. It is assumed that the space requirement is very small and cannot be used otherwise. The oil tank for the decentralised oil boilers in the cluster of exiting buildings are weighted with 5 %, since it is assumed that the space inside the buildings could be possibly used for e.g. storage areas.

5.4.2 Flexibility in future power-to-heat systems (potentials for P2H)

The increasing share of fluctuating RES, like photovoltaic (PV) and wind energy, in the electricity mix is a major challenge for the energy systems in general. Particularly in times when a lot of PV or wind power is generated, the produced electricity cannot be consumed at that time and the transportation capacities are too limited to transport the electricity to other users. To overcome this challenge of temporary "surplus energy", the coupling of the electricity and heat sectors are one feasible option (Schmidt et al. 2015; Yu 2013). This strategy is also known as "power-to-heat" (P2H). In the context of P2H, in particular renewable-based district heating systems offer great potentials since large amounts of energy can efficiently be stored in the grid or central heat storages. For example, combined heat and power systems (CHP), electric heaters and heat pumps can be used as connection technologies between the electricity and heat market to provide both power supply and to process price signals of the electricity market (Huenges et al. 2014). For that reason "flexibility options" in the electricity system as well as the possibilities of the heat market to stabilise the electricity market have to be taken into account for an efficient sector coupling.

As one work package of the research project "Wolfhagen 100% EE "(Wagner, Both 2016) the hourly distribution of electricity surplus in the electricity grid of the city of Wolfhagen was measured. As part of (Yu 2014) the potential contribution of surplus renewable electricity supply and the heating demand of a single-family house was modelled. The data in Figure 5-8 shows that a direct use of surplus electricity without storage is not a favourable solution because of a significant timely mismatch. It can be concluded that power-to-heat solutions demand the integration of thermal storage capacity such as water storages or district heating grids.

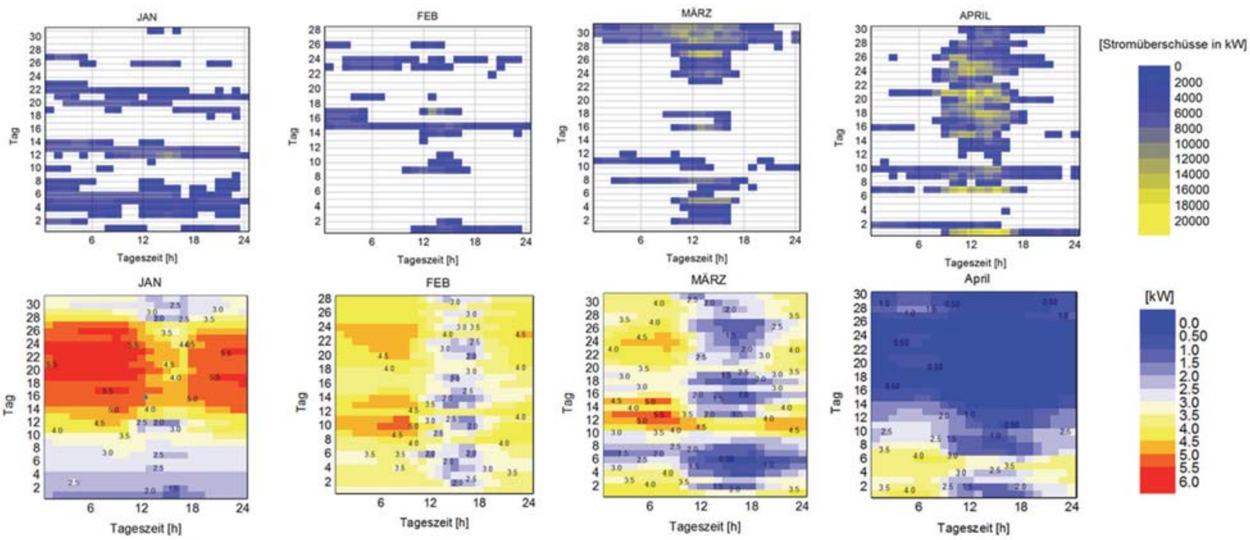


Figure 5-8: Top: Hourly distribution of electricity surplus in the Wolfhagen grid. Bottom: Heating energy demand of a single-family house (Yu 2014).

At a first glance, P2H is not a good solution from an exergetic point of view, since the overall working potential of the energy flow cannot be used. However, in the case of the application of P2H technologies, it must be taken into account that the central objective of the energy transition is the decarbonisation of the total energy systems by using electricity from 100 % RES (Gerhardt et al. 2015). In turn it is not aimed to increase the share of the renewables due to the flexibilization by producing excess electricity. From an exergetic point of view, the grid extension is the more favourable solution compared to P2H. This is not in all cases possible. As a result, the electricity from renewables is only used for heating purposes if the surplus electricity would otherwise have to be curtailed. The main task of the exergy assessment of P2H is to support the "supply-adapted demand", in case if electricity is used for heating purposes. Furthermore in many cases, conventional fuels (coal, gas, oil, etc.) are saved. The basic idea of the exergetic evaluation thus corresponds to the basic idea of the P2H to use energy resources carefully and economically.

Furthermore, an approach has been discussed in chapter 2.5, which allows distinguishing between electricity from fossil and renewable energy sources. As part of this thesis, this approach is used for the assessment of auxiliary energy (pumping power) and electricity for heating purposes. In principle, the approach shows great potential for the evaluation of power-to-heat technologies. However, the final evaluation is not be done within this work.

Within the scope of this work, only a rough estimation of the flexibility potentials of energy suppliers is done as part of the investigated scenarios. As a result, it is estimated to what extent the investigated scenario has the potential to contribute to the rationalisation of the future energy system. The "flexibility potential" is used as a "Soft Evaluation Factor" (see chapter 5.4.2). The flexibility potential can be used to quantify the "asset" or the "ability" of an energy supply concept (including energy suppliers and storages) to offer flexibly to the electricity market and / or to the electrical grid, supporting the integration of RES. The factor does not yet take into account seasonal fluctuations or the actual electricity market situation or the transportation capacities of the grid. The approach is being discussed in section 7.4.2.

6 Definition of generic case studies

Based on the assumptions found in chapter 4 and the correspondingly determined energy demand, different decentralised and centralised supply options (scenarios or generic cases) and several sub-variants (supply variants) for a cluster of new and existing buildings (single family houses) are developed.

The selection of these different generic cases is based on an extensive literature research respectively the analysis of national and international best practice examples (e.g. (Sipilä, Rämä 2016; Eicker 2012; Schmidt et al. 2017)). Since the focus is on renewable energy based district heating supply, the utilization of near-surface geothermal energy by means of borehole heat exchangers (BHE), the use of solar energy and a methane powered CHP are selected to be suitable energy sources. The different generic case studies are analysed as part of a technology comparison in chapter 7.

6.1 Design of the individual buildings as part of the building group

The main assumptions of the buildings implemented in the building group (in the following also referred to as "cluster") are introduced as part of chapter 4.2. The buildings differ in case of their user profiles (see chapter 4.3) and in case of their energy demand (see Table 6-1).

Table 6-1: Overview of the properties of the buildings (new and existing buildings) as part of the building groups.

				New buildings		Existing buildings			
Unit	Profile	PWH (45 °C)		Space heating	Hot water	Building age	Level of renovation	Space heating	Hot water
[-]	[-]	l/(Pers*d)	l/d	kW	kW	[-]	[-]	kW	kW
A1	Average	35	140	6.5	7.8	1978-	Present	11.1	7.8
L3	Low	20	60	5.5	7.16	1978+	Present	13.6	7.16
L1	Low	20	80	5.5	7.04	1978-	Present	7.1	7.04
L2	Low	20	100	5.5	7.6	1995+	Good	4.8	7.6
A2	Average	35	105	6.5	7.28	1978-	Present	11.2	7.28
A3	Average	35	140	6.5	7.44	1995+	Good	6.4	7.44
H1	High	35	175	6.5	8.96	1978-	Present	15.7	8.96
H2	High	60	180	8.5	8.44	1978+	Very good	6.8	8.44
H3	High	60	240	8.5	11	1978-	Present	10.9	11
H4	High	60	300	8.5	10.2	1978-	Present	17.9	10.2

The surfaces and U-values of the opaque and transparent building components as well as emission systems of the ten buildings of the new buildings cluster are identical. In contrast the ten buildings of the existing buildings cluster are assigned by different building age classes based on statistical values for Germany according to (Loga et al. 2015). Accordingly, the distribution of the building age classes is as follows: 1978- (63 %), 1978+ (19 %) and 1995+ (18 %). In relation to the ten buildings, six buildings arise for 1978- and two buildings for both 1979+ and 1995+. In this way the municipal building stock is depicted. The three levels of redevelopment (see also chapter 4.2) are assigned to the ten buildings by taking assumptions of (Kohler 2016) into account.

6.2 Decentralised supply D (reference scenarios)

Main purpose of the decentralised scenarios is the comparison of centralised and decentralised supply variants as reference. Correspondingly standard solutions based on combustion processes and a renewable-based solution for individual building supply are compared to innovative, heating network-based supply solutions (see also technology comparison in chapter 7).

The decentralised supply options are designed taking into account the user behaviour and the corresponding energy demand for space heating and PWH supply (see also Table 6-1) of each single building. As part of the decentralised scenarios the following three main scenarios were developed.

- **D1 natural gas boiler (NG boiler):** As part of this scenario a natural gas boiler (NG boiler) is investigated, which is typically found in new buildings (Loga et al. 2015). It should be noted that due to the German law "EEWärmeG" (BMWI 2016c) the NG boiler has to be combined with a renewable energy supplier (e.g. solar thermal collectors for PWH supply). Since the investigations are aimed at the comparison of decentralized fossil fuels-based supply unit to renewable based LTDH supply, the consideration of a further energy source has been dispensed in this context.
- **D2 ground source heat pumps (GSHP):** In this scenario ground source heat pumps (GSHP) are selected for comparison of a renewable energy supplier to the LTDH supply solutions.
- **D3 oil boilers:** As part of scenario D3 an oil boiler is selected, which is typically found in existing buildings (Loga et al. 2015).

The following chart shows an overview of the selected decentralized supply variants for new building cluster and existing buildings cluster.

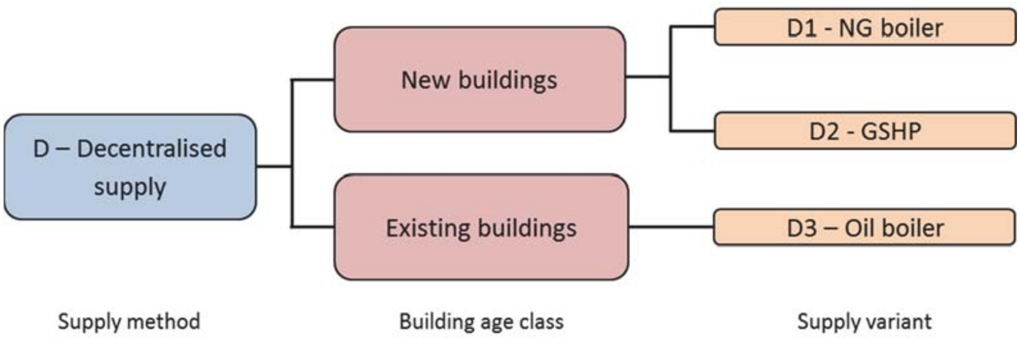


Figure 6-1: Overview of the decentralised supply options for new buildings (D1 and D2) and existing buildings (D3).

To supply the NG boilers with natural gas, a gas grid is regarded in scenario D1. In comparison to scenario D1, in the course of the scenario D2 and scenario D3 no gas grids are regarded (for further discussion of this assumption see also chapter 5.4.1).

6.3 Centralised supply of the building cluster

By using a model of a cluster of ten buildings, different supply scenarios are developed for examination (Figure 6-2). As part of the selection of suitable examination variants a distinction is made between new and existing buildings like in the decentralised variants. The new buildings cluster consists of identical buildings with a high energetic standard. The buildings as part of the cluster of existing buildings differ in terms of their building age class. The characteristics of the single buildings implemented in the cluster are found in Table 6-1 in chapter 6.1.

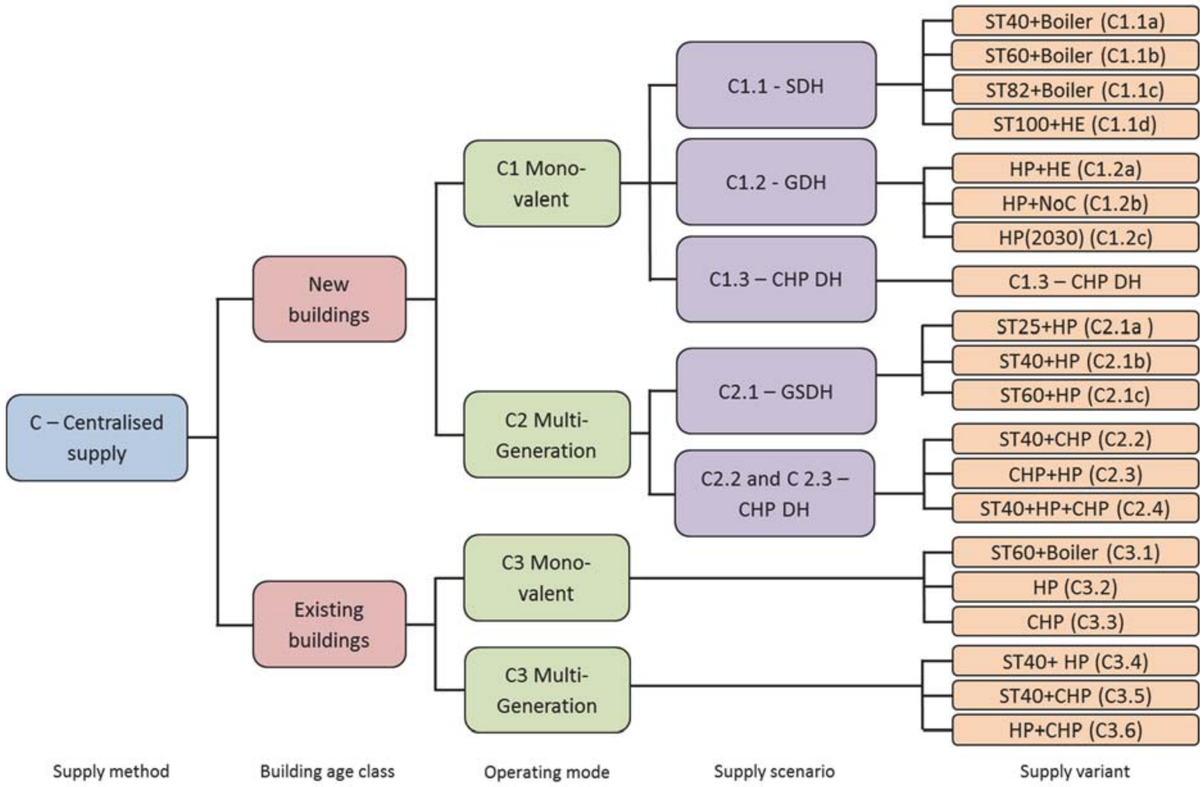


Figure 6-2: Overview of the centralised supply options for new buildings (C1 and C2) and existing buildings (C3).

For both the new and the existing buildings cluster, the operating mode is differentiated in monovalent and multi-generation supply. In case of monovalent supply for the new buildings (C1) three supply scenarios are investigated, where the suppliers are considered individually. In this variant, the heat is mainly provided by solar thermal collectors (ST) supported by a peak load boiler, ground source heat pumps (GSHP) or a CHP unit. A variation of the solar fraction ("STxx") and supply strategy (e.g. deactivation of the thermal network in summer) results in further eight subvariants. In the course of the supply variants of the multi-generation supply scenarios (C2), the generation units of the monovalent variants are combined. As part of further variations, different solar coverage rates are investigated for six different combinations (supply variants). In the course of simplification, all supply scenarios of the existing buildings are referred to as C3. In case of monovalent supply for the existing buildings, three supply variants, solar thermal collectors (ST) supported by a peak load boiler, ground source heat pumps (GSHP) and a CHP unit, are examined. As part of multi-generation supply three selected supply variants are investigated.

With regard to suitable supply temperatures as part of preliminary simulation studies, it turned out that a supply temperature of 45 °C for the new buildings and a supply temperature for the existing buildings of 75 °C are optimal. These temperature levels represent the lowest possible temperature level to ensure secure of supply and user-comfort (both space heating and PWH). Furthermore the values are consistent with values that can be found in the literature (e.g. (Brand 2014)).

6.3.1 Monovalent supply for new buildings (C1)

The cases of C1 are serving for the comparison and evaluation of different supply scenarios by using different energy sources for centralised LTDH. As supply units solar thermal collector arrays, ground source heat pumps and a CHP unit are selected. The supply units are operated mainly monovalent. As main parameters for comparison a varying solar coverage (solar fraction) as well as the management of circulation in the thermal grid and the electricity mix are investigated. By taking these assumptions into account, the following three main scenarios are developed (see Table 6-2).

- **C1.1 Solar district heating (SDH):** As part of the SDH scenarios, several concepts of solar district heating (SDH) for a new buildings cluster are investigated. For the selection and design of the system configurations, different best-practise examples are evaluated (see chapter 4.8.1). The investigations are aimed at the estimation of the influence of solar fraction. For that reason the scenarios differ in collector size as well as type and volume of the storage device. As part of the first four scenarios, C1.a-C1.c, a peak load boiler is implemented. In scenario C1.1d a solar fraction of 100 % is investigated (without peak load boiler). In the event that energy demand is nevertheless not achieved, a heating rod is installed. In order to reflect the different generations of district heating (Lund et al. 2014) and to quantify the influence on heat supply and performance of the system the temperature level of selected system variants is varied between 45…75 °C [17].
- **C1.2 Geothermal district heating (GDH):** In these scenarios a central heat pump (GSHP, monovalent) with a geothermal field as heat source is used for supply. The main assumptions are found in chapter 4.8.2. The difference between the configurations results from the handling of the circulation of the local heating network in the summer as well as the consideration of another electricity mix (higher share of renewables). In "HP+NoC[18] (C1.2b)" the network circulation is switched off during the three summer months. The energy for heating the hot water comes from the heating rods in the buildings. In this scenario fewer thermal losses (network and storage) and lower electricity consumption (compressor of the heat pump and circulation pumps) are expected. The supply variant "HP (2030) (C1.2c)" is used to quantify the influence of the electricity mix of the German power plant park in 2030. A positive influence on the selected assessment factors is expected.
- **C1.3 CHP DH:** The heat (space heating and PWH) in this scenario is supplied by a monovalent cogeneration unit, which heats a central storage tank. The local heating network is fed from the buffer storage. The CHP must ensure a minimum temperature of 45 °C in the storage tank. The main assumptions are found in chapter 4.8.3.

As part of the technological analysis in chapter 7 the variants of the monovalent scenarios (C1) are compared to each other and to the decentralised scenarios D1 and D2. The main issue in this context is to highlight the advantages or disadvantages of the energy suppliers. Furthermore the question needs to be answered if it is possible to supply new buildings by renewable energy with a temperature level of ultra-low temperature district heating (ULTDH) supply (≤ 50 °C) (Østergaard, Svendsen 2017).

[17] An investigation of varying supply temperatures in other scenarios was dispensed with since the results were almost proportional.

[18] NoC= No circulation during three month in summer.

Table 6-2: Scenarios for investigationof centralised supply for new building group (C1).

		Solar district heating (SDH)				Geothermal district heating (GDH)			CHP DH (C1.3)
		ST40+Boiler (C1.1a)	ST60+Boiler (C1.1b)	ST82+Boiler (C1.1c)	ST100+HE (C1.1d)	HP+HE (C1.2a)	HP+NoC (C1.2b)	HP(2030) (C1.2c)	
Temperature level DH ($T_{supply,DH}$)	°C	45	45	45	45	45	45	45	45
Variation temperature level ($T_{supply,DH}$)	°C	-	-	-	60, 75	-	-	-	-
Solar fraction (f_{sol})	%	40	60	82	100	-	-	-	-
Collector size area (A_{coll})	m²	280	470	600	800	-	-	-	-
Peak load boiler ($P_{peak,th}$)	kW_{th}	60	60	60	-	-	-	-	-
GSHP ($P_{GSHP, th}$)	kW_{th}	-	-	-	-	60	60	60	-
Seasonal performance factor (SPF) GSHP	-	-	-	-	-	4	4,3	4	-
Number BHE (n_{BHE})	-	-	-	-	-	12	12	12	-
CHP (thermal load) ($P_{CHP,th}$)	kW_{th}	-	-	-	-	-	-	-	60
Seasonal storage (V_{SS})	m³	450	750	1200	1700	-	-	-	-
Storage tank (V_{ST})	m³	20	20	20	20	20	20	20	20
Circulation (summer time)	-	-	-	-	-	-	NO	-	-
Electricity mix (year)	-	-	-	-	-	-	-	2030	-
Master pump DH (P_{grid})	W_{el}	650	650	650	650	400	400	400	650
Pump solar circuit ($P_{max\ Sol}$)	W_{el}	175	175	250	350	-	-	-	-
Pump BHE ($P_{max\ BHE}$)	W_{el}	-	-	-	-	165	165	165	-
Pump CHP ($P_{max,CHP}$)	W_{el}	-	-	-	-	-	-	-	175
Pump storage circuit ($P_{max,Stor}$)	W_{el}	40	40	60	80	40	40	40	40

6.3.2 Multi-generation supply for new buildings (C2)

As part of the cases of scenario C2, multi-generation supply is regarded. In order to assess the benefits of merging several renewable energy suppliers, different renewable energy supply units are regarded in two- or three-unit combinations. The following two main scenarios are developed:

- **C2.1 Geosolar district heating (GSDH):** As part of this scenario the solar thermal collectors are combined with a GSHP. Like in C1.1 the collector size area and volume of the storage device are varied. In contrast to the cases of solar district heating, the peak load boiler is replaced by a GSHP. The advantages and disadvantages of the GSDH supply are to be shown by a comparison with the corresponding variants. Furthermore a variation of the supply temperature is performed (see also scenario C1.1d).
- **C2.2-4 CHP district heating:** In the course of the CHP it is aimed to show the advantages and disadvantages of combining one or two additional energy suppliers with the CHP units. Due to economic reasons, a priority circuit is assumed for the CHP (Kabus 2014).

All centralized supply options (scenarios) including the sub-variants (supply variants) for multi-generation are shown in Table 6-3.

Table 6-3: Scenarios for investigationof centralised multi-generation supply for a gourp of new buildings (C2).

		Geosolar district heating (GSDH)			CHP district heating (CHP DH)		
		ST25+HP (C2.1a)	ST40+HP (C2.1b)	ST60+HP (C2.1c)	ST40+CHP (C2.2)	CHP+HP (C2.3)	ST40+HP+CHP (C2.4)
Temperature level DH ($T_{supply,DH}$)	°C	45	45	45	45	45	45
Variation temperature level	°C	-	60, 75	60, 75	-	-	-
Solar fraction (f_{sol})	%	25	40	60	40	-	-
Collector size area (A_{coll})	m²	200	350	500	350	-	350
GSHP (power)	kW	60	60	60	60	45	45
Number BHE (n_{BHE})	-	12	12	12		12	10
CHP (thermal load) ($P_{CHP,th}$)	kW	-	-	-	60	20	20
Seasonal Storage	m³	300	490	850	490	-	490
Storage Tank	m³	20	20	20	20	20	35
Master pump DH (P_{grid})	W_{el}	650	650	650	650	650	700
Pump solar circuit ($P_{max\ Sol}$)	W_{el}	175	175	175	40	-	40
Pump BHE ($P_{max\ BHE}$)	W_{el}	165	165	165	-	85	85
Pump CHP ($P_{max,CHP}$)	W_{el}	-	-	-	100	35	35
Pump storage circuit ($P_{max,Stor}$)	W_{el}	40	40	40	40	85	40

In the course of the technological analysis in chapter 7, the variants of the multi-generation supply scenarios (C2) are compared to the variants of the monovalent scenarios (C1) as well as the decentralised scenarios D1 and D2. The main issue in this context is to derive advantages or disadvantages of the combination of energy suppliers.

6.3.3 Centralised supply of existing buildings (C3)

The new construction rate is just below 1% referring to the entire building stock in Germany. For that reason in particular the building stock offers high potential for increasing efficiency while simultaneously reducing GHG emissions (Li, Svendsen 2012) and is therefore part of further investigations in this work. In order to depict the building stock, the assumption of profiles, building age and level of renovation are selected for each building according to Table 6-1. In the simulation supply units are used in six different variants: solar thermal collectors, GSHP and CHP. In the course of the investigations on solar fraction, an ambitious solar coverage of 60 % is implemented for the building stock. The scenarios are designed in accordance with the previously described design rules and are represented in Table 6-4.

Table 6-4: Scenarios for investigation of centralised multi-generation supply for existing building group (C3).

		ST60+Boiler (C3.1)	HP (C3.2)	CHP (C3.3)	ST40+ HP (C3.4)	ST40+CHP (C3.5)	HP+CHP (C3.6)
Temperature level DH ($T_{supply,DH}$)	°C	75	75	75	75	75	75
Collector size area (A_{coll})	m²	900	-	-	500	500	-
Peak load boiler (P_{peak})	kW_{th}	100	-	-	-	-	-
GSHP (power) (P_{GSHP})	kW_{th}	-	114	-	114	-	76
Number BHE (n_{BHE})	-	-	24	-	16	-	16
CHP (thermal load) ($P_{CHP,th}$)	kW_{th}	-	-	100	-	100	38
Storage tank (V_{ST})	m³	35	35	35	35	35	35
Seasonal storage (V_{SS})	m³	4 200	-	-	850	850	-
Master pump DH (P_{grid})	W_{el}	650	650	650	650	650	650
Pump solar circuit ($P_{max\ Sol}$)	W_{el}	175	175	175	40	40	-
Pump BHE ($P_{max\ BHE}$)	W_{el}	165	165	165	165	-	85
Pump CHP ($P_{max,CHP}$)	W_{el}	-	-	-	-	100	35
Pump storage circuit ($P_{max,Stor}$)	W_{el}	40	40	40	40	40	85

The variants of the cluster of existing buildings (C3) are compared to each other and to the corresponding variants of the cluster of new buildings (C1 and C2) in the course of the technology comparison in chapter 7. Furthermore the variants of C3 are compared to the reference variant D3 (oil boiler). Main issue of the case studies examined is to figure out if and to which extend it is possible to supply the German building stock with LTDH solely based on renewables. Furthermore the combination of different supply units (multi-generation) is investigated.

7 Results of the technology comparison

As part of this chapter a technology comparison of different supply scenarios is carried out, which are defined as part of chapter 6. Accordingly different centralised and decentralised supply scenarios (supply concepts) of a cluster of new buildings[19] (C1 and C2) and a cluster of existing buildings[20] (C3) are investigated in a comparative analysis.

The energy supply scenarios are assessed based on the Hard Evaluation Factors (HEF) and the Soft Evaluation Factors (SEF) defined and introduced in detail as part of chapter 5 (see also Figure 5-1 on page 41). The evaluation is carried out by taking the parameters individually and simultaneously into account. In this way, the most suitable supply option can be identified taking only one or all factors into account. The overall target of the technology comparison is to demonstrate the usability of the exergy-based assessment method, which is introduced as part of chapter 3 and chapter 5. Another aim is to test the hypothesis that the application of exergy as sole evaluation parameter highlights the importance and necessity of demand-adapted supply, but the combination with selected evaluation parameters increases the added value of exergy-based assessment of energy systems.

The calculations are carried out in in accordance to (VDI 2067 2012; DIN V 18599-1:2016-10; GEMIS 2016) for that reason a technical standard of the year 2016 is reflected in all scenarios. A detailed overview of the simulations results, which provide the main basis of this technology comparison, is given in the appendix B1.

7.1 Energy efficiency and overall exergy efficiency

In this section energy efficiency η and overall exergy efficiency ψ are chosen for evaluation, since these factors appear to be the most suitable for the direct comparison (see also discussion in chapter 5.1). However, it should be noted that the factors from the first glance are difficult to compare with regard to their "quantitative" values. The best energy efficiency results are about 100 % while the best results (e.g. condensing boilers) for overall exergy efficiency are about 25 % (e.g. direct use of waste heat). A conversion, e.g. by using sustainability factors (Dincer, Rosen 2013), is not included in this work, since an independent consideration of both physical quantities should remain possible.

As part of the evaluation the overall efficiencies of the clusters are compared (for definition see see chapter 5.1). A detailed evaluation of the energy and exergy flows occurring in each component of energy chain (see also Figure 3-1 in chapter 3) is found in the appendix B in section B3.

7.1.1 Evaluation of supply for new buildings (scenario C1)

The comparison of energy efficiency η of centralised supply (scenarios C1) and decentralised respectively reference scenarios (D1 and D2) for the new buildings is shown in Figure 7-1. The comparison of centralised supply and the reference scenarios leads to the conclusion that the "NG boiler (D1)" is the favoured solution in case of energy efficiency η. Also the decentralized heat pump "HP (D2)" is advantageous compared to the solar district heating variants (SDH) but also to

[19] New buildings = building aligned to present-day demands (2015)
[20] Existing buildings = Buildings with properties according to older practice

the monovalent HP (supply variant C1.2a and C1.2b). This result is attributable to the high efficiency (seasonal performance factor SEF) of the heat pump (SPF= 4 - 5) and the thermal losses mainly resulting from the storage devices but also a small part from the thermal network.

But particularly in new housing areas the implementation of renewable energy sources (RES) is mostly targeted due to further restrictions (e.g. reduction of CO_2 emissions or the presence of an urban ventilation path (Schmidt et al. 2017)). In this context heating grids offer advantages, since the combination of different energy sources is possible. The scenarios of SDH show only a low degree of energy efficiency and provide only little incentive for implementation. This reduction in energy efficiency is in particular due to the fact that the thermal losses increase by approximately 90 % in the overall system (in particular in seasonal storage) with increasing solar fraction from 40 % to 82 %. In contrast, the electrical energy consumption (pumps and heating rod) is reduced by 10 % and the consumption of the peak load boiler drops by 28 %. The lowest energy efficiency is achieved by the "ST100+HE" due to the high overall thermal losses in the energy system. In turn the CHP unit has the highest energy efficiency with 80 % in case of the centralised supply and in accordance with (DIN V 18599-1:2016-10; Hertle et al. 2014).

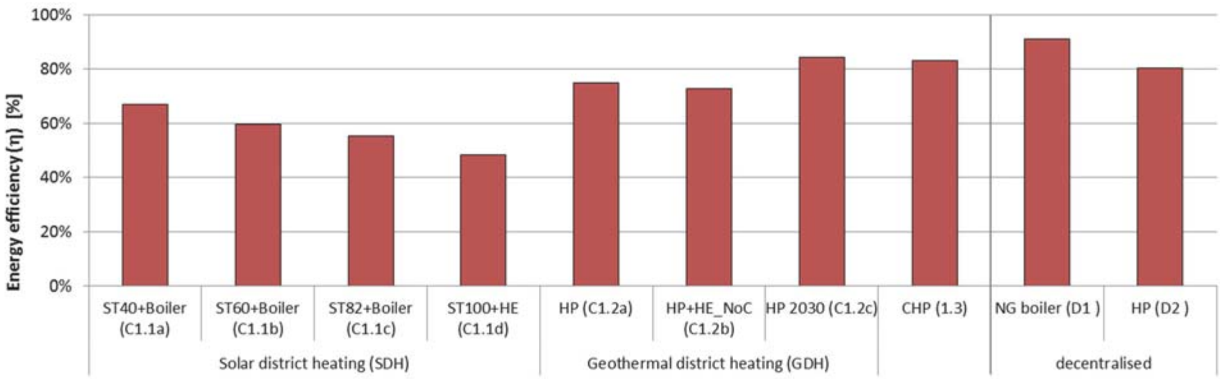


Figure 7-1: Energetic evaluation of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

In case of geothermal district heating (GDH), the comparison of decentralised (HP (D2)) and the centralised heat pump (HP (C1.2a)) shows, that the decentralised "HP (D2)" from the perspective of energy efficiency scores a bit better. This is mainly since the energy losses in the centralised system (e.g. storage or grid) are a bit higher that in the decentralised system. Based on this result, a small disadvantage of the decentralized supply by using a heating network can be derived. When considering the results, it should be noted that the overall system efficiency of the supply system is included in the assessment. Hence the efficiency of providing space heating and DHW is taken into account for the overall evaluation.

Unlike initially expected, the deactivation of the circulation in summer "HP+HE_NoC (C1.2b)" has only a small positive effect on energy efficiency (< 1 %), since the entire system must be re-heated at the beginning of the heating period. For reheating, the thermal inertia of the grid has to be overcome whereby the required compressor capacity exceeds the saved power (heat pumps and circulation pumps). However, this result must also be viewed critically. If for example solar thermal energy were available for the preheating of the grid, this effect would possibly be less strongly pronounced. As part of scenario "HP 2030 (C1.2c)" it is shown that the electricity mix has a positive impact on the energy efficiency of the heat pump. Nonetheless this scenario is not directly comparable to the other scenarios since primary energy factor according to (DIN V 18599-1:2016-10) are used. The increased efficiency is traced back to the expected increasing primary energy factor (f_P = 0.8) of the electricity mix of the year 2030 (Stawiarski 2013; SBZ 2012). Nevertheless this scenario shows that high efficient GSHP have high potential to become a key technology in future energy supply using local low temperature heating grids.

When taking exergy efficiency ψ into account the results of the analysis change significantly (Figure 7-2). From an exergetic point of view the decentralised NG boiler is not a good supply option, since high quality fuels are burned and therefore the temperature level of potentially available heat (flame temperature) to heat the room air is too high. As a result high exergy destruction occurs. In comparison to the NG boiler (D1), the exergy efficiency of the decentralised GSHP (D2) is about 5 % higher. This is mainly due to the good SPF of more than 4 where a part of the required heating energy is provided by low-quality geothermal energy and the exergy destruction is reduced accordingly.

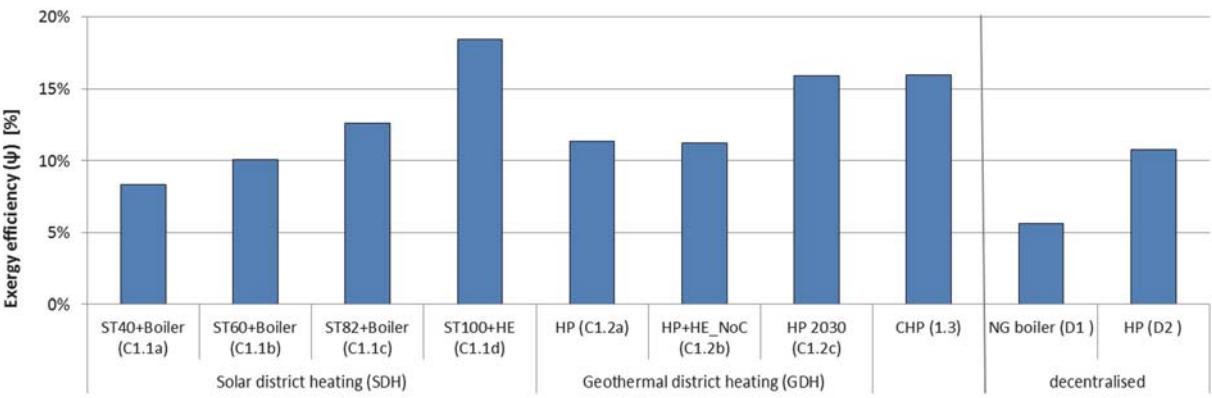


Figure 7-2: Exergetic evaluation of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

In contrast to the energy assessment the exergy assessment of the solar district heating (SDH) variants demonstrates that the higher the solar fraction, the higher the exergy efficiency. Since the exergy analysis considers the working potential in relation to the selected reference environment (Torio, Schmidt 2011). The working potential (quality) of the heat coming from the solar thermal collectors is considerably smaller in comparison to working potential of electricity or natural gas (see also chapter 2.1). In case of increasing solar fraction, the amount of low valued solar thermal energy increases while the amount of high quality sources consumed by the peak load boiler and the heating rods decreases significantly (see also Figure B-7 on page 121). As a result, the exergy efficiency increases significantly by the decreasing exergy destruction. The comparatively small increase of the electricity demand of the pumps (4 %) is replaced by the significant reduction of demand of natural gas (methane) for the boiler (28 %) and the electricity for the heating rods (6 %). Even if the thermal losses in SDH variants from the perspective of energy efficiency are comparatively high, the exergy destruction is rather low due to the low quality of the energy within the thermal fluids. Nevertheless, in particular in larger energy systems with higher supply temperatures, these exergy losses should not be neglected, since they also offer high potential for further improvement of the system.

The best performance with regard to exergy efficiency is shown in "ST100+HE (C1.1d)". The majority of the heat demand can be covered by the solar collectors in combination with a large seasonal storage. Only during the heating period, heating rods are required, but they account for a comparatively small proportion of the total annual heating demand. However, it should be noted critically that the realization of a 100 % solar coverage can only be realized in very small heating systems where the building energy standard is very high and the supply temperatures in the local heating grid is very low (< 50 °C) (Hilz 2010).

When comparing the decentralised heat pumps (HP (D2)) to the centralised supply variants, the decentralised HP shows advantages over the SDH variants with a solar fraction less that 60 % and using a peak load boiler. Like the solar collectors in the SDH variants also the GSHP uses a high amount of low qualitative energy (near-surface geothermal heat) for providing heat due to the high SEF. But also both supply variants, SDH and GDH, are using high quality energy sources (electricity and natural gas) to cover the heating demand of the buildings. In contrast to the solar radiation the geothermal heat of approximately 10 °C is available during the whole year which becomes clearly visible in terms of the results.

In relation to the centralised HP the exergy efficiency of the decentralised heat pump is 2 % lower. This result is mainly due to the additionally required compressor power of the single heat pumps, which require 8 % more electricity in total. The overall comparison of the GDH variants shows small advantages for implementation of GDH supply in comparison to the monovalent heat pumps.

The comparison of the centralised heat pump “HP (C1.2a)” to the scenario “HP+HE_NoC (C1.2b)”, where the circulation during summer time is switched off, leads to the conclusion that the exergy efficiency decreases by 0.5 %. This is justified by the fact that during summertime the PWH demand has to be covered by heating elements, which requires 100 % electrical energy (heating element). Additionally a high compressor output is necessary for reheating the system for a short period of time. As a result the exergy destruction in this scenario increases which has negative impact on the exergy efficiency. Furthermore, a positive effect with respect to the electricity mix (SBZ 2012; Gerhardt et al. 2015) in sub scenario “HP+HE (2030) (C1.2c)” can also be observed from an exergy point of view. Thus, potential benefits of the heat pump are shown when the share of renewable energies in the electricity mix increases. By incorporating the composition of the electricity mix, exergetic advantages can also be derived consistently. However it should be noted critically that this approach allows the comparison with other scenarios only to a limited extent.

The evaluation further shows, that CHP “CHP (C1.3)” has a good exergetic efficiency of more than 16 %. This result is explained by the application of the Carnot-method (Hertle et al. 2014). The method allocates fuel input to the generated heat and electricity. Based on this method, the exergy content of the output of the CHP is regarded, which results in a comparatively good exergy efficiency (Jentsch 2010).

7.1.2 Evaluation of multi-generation for new buildings (scenario C2)

Basically the evaluation of the multivalent supply (scenarios C2) leads to partially similar conclusions like the analysis of scenario C1 (Figure 7-3). As it can be seen the NG boiler is the most energy efficient supply technology since a high amount of the fuel is available to supply the buildings. Like in C1 the energy efficiency of the supply scenarios decreases with rising share of solar energy due to the increasing overall thermal losses in the system. The highest efficiency is achieved by “CHP+HP (C2.3)”.

In comparison to the corresponding SDH scenarios using peak load boilers, the efficiency of the geo-solar district heating variants drops by approximately 4 %. The scenarios of the CHP district heating (CHP DH) show similar results. The result can be attributed to the selected, different primary energy factors for fossil fuels (natural gas $f_P = 1.1$) and electricity ($f_P = 1.8$) (DIN V 18599-1:2016-10). If the factors of the electricity are reduced by the increase of the share of renewable energies in the German electricity mix (SBZ 2012; Gerhardt et al. 2015), it can be expected that the geo-solar variants would be significantly more competitive in future energy systems (see also discussion of sub scenario "HP 2030 (C1.2c)" in previous section 7.1.1). The comparison of the CHP DH to the monovalent CHP unit (C1.3), where the CHP is combined with a GSHP "CHP+HP (C2.3)" or a GSHP and solar collectors "ST40+HP+CHP (C2.4)", leads to the conclusion that the combination of renewable energy suppliers has no advantages taking energy efficiency into account. This result is mainly attributable to the used primary energy factor f_p (DIN V 18599-1:2016-10) and the thermal losses.

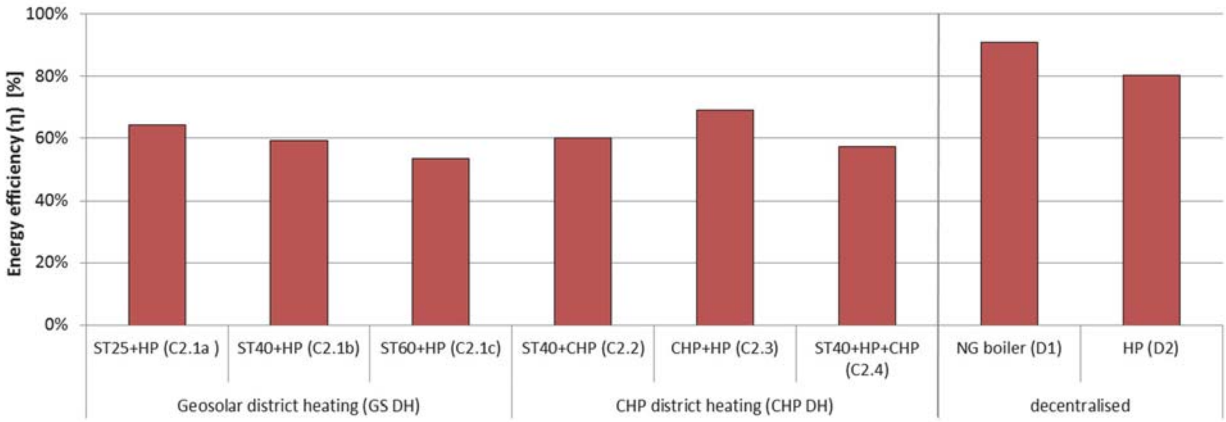


Figure 7-3: Energetic evaluation of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

From the results it can be concluded that the combination of several renewable energy sources has no advantage in terms of energy efficiency.

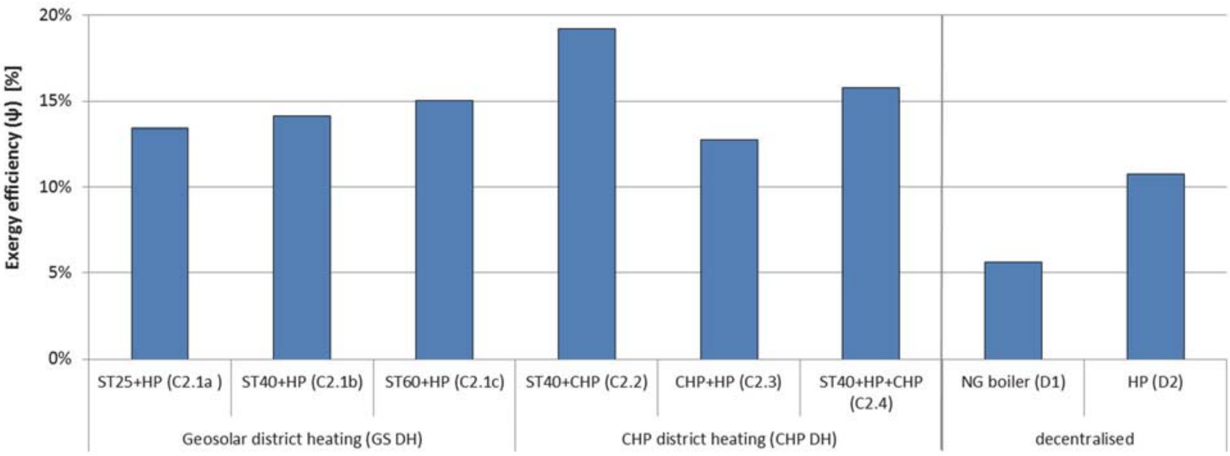


Figure 7-4: Exergetic evaluation of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

By taking exergy efficiency into account, the picture changes significantly again (see Figure 7-4). As shown as part of exergetic evaluation of scenario "ST+Boiler (C1.1)" (solar thermal collectors and peak load boiler), the exergy efficiency increases if the solar fraction rises. In the case where the solar collectors are combined with heat pumps "ST+HP (C2.1)" instead of peak load boilers, the exergy efficiency increases by 6 % in average. This can be explained by the fact that this option is using high quality sources from fossil fuels (electricity) but also low valued environmental energy (geothermal energy). In contrast the boilers are only using high quality sources, such as methane and electricity (reheating and auxiliary energy). Furthermore the quality factors β_{LHV} (Hepbasli 2008a) for the electricity mix and methane (simplified used for natural gas) differ only slightly. From this circumstance, an advantage for the exergetic analysis is obtained.

With regard to the CHP DH variants, the exergy efficiency increases by 4 % if the monovalent CHP is combined with solar thermal collectors. The overall comparison also shows that this variant has the best performance. In case where the monovalent heat pumps are combined with CHP or with CHP and solar thermal collectors, the exergy efficiency increases. This result is mainly explained by the application of using the Carnot-method (see previous section). In contrast, the combination of a "CHP (C1.3)" with a heat pump has no advantages. The overall comparison of C1 and C2 from an exergy point of view leads to the conclusion that the combination of different renewable energy suppliers is advantageous in most cases.

7.1.3 Variation of supply temperature for new buildings

As mentioned in chapter 6, the temperature level for selected scenarios is increased gradually in 15 °C steps; from 45 °C to 75 °C. In this way the influence of rising supply temperatures on the energy and exergy efficiency is evaluated.

In case of energy efficiency η the simulation results of the geo-solar supply variants (ST+HP (C2.1)) show that increasing use of solar thermal energy and the increase of the supply temperature have a rather negative impact of the energy efficiency (see Figure 7-5).

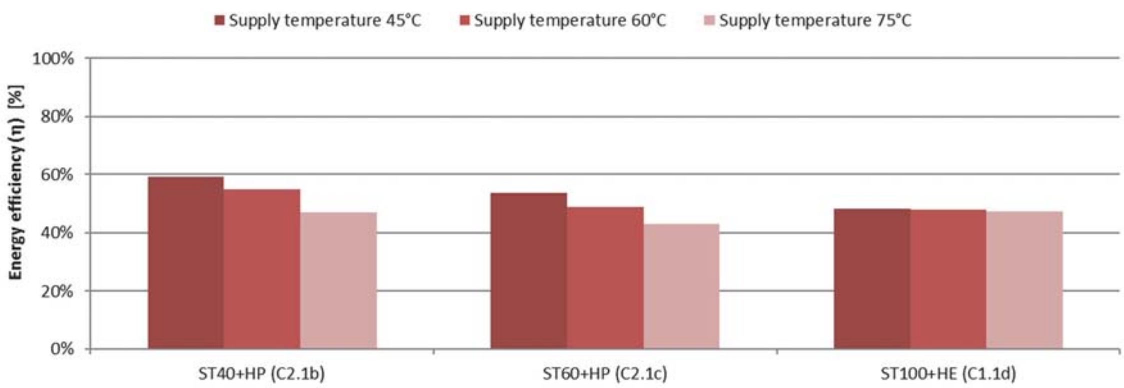


Figure 7-5: Assessment the influence of rising supply temperatures on the energy efficiency for selected supply scenarios.

The result is in particular due to the high thermal losses in the collector circuit (solar system) and in the storages as well as the decreasing solar fraction and the decreasing SPF with increasing required temperature level. In the case of the supply variant "ST100 + HE", the influence of the rising temperature level on the energy efficiency is rather low. This result is due to the fact that the solar yield is roughly the same in all cases, which means that thermal losses (especially in the seasonal storage) are approximately equal.

Also the simulation result of the exergy efficiency ψ of the geo-solar supply variants (ST+HP (C2.1)) decreases (see Figure 7-6). However the effect is more pronounced, since the energy suppliers must provide more high-valued electrical energy to provide the higher supply temperature and to compensate the increasing thermal losses in the grid. As a result exergy destruction increases in the whole system. In contrast to the energy efficiency the exergy efficiency increases by 5 % in total in scenario "ST100+HE (C1.1d)" when the temperature increases. This result indicates very high exergy destruction in scenario "ST100+HE (C1.1d)" when a supply temperature is selected. In contrast, when a set-point temperature of 75 °C is selected, the running time of the heating elements (HE) is reduced from 5201 h/a to 942 h/a, even if higher mixing losses are occurring for space heating (see Figure B-7 on page 122). Furthermore in this context the seasonal storage has a positive impact on the running time due to its large volume.

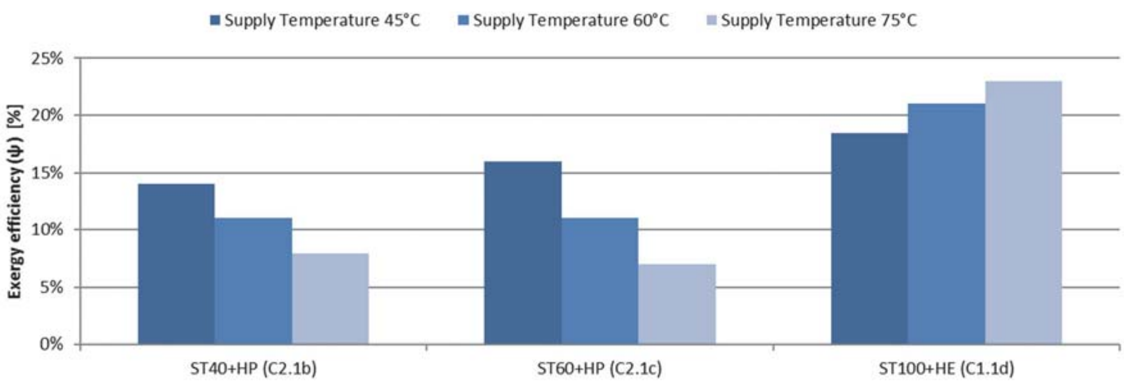


Figure 7-6: Assessment the influence of rising supply temperatures on the exergy efficiency for selected supply scenarios.

The result of this analysis highlights that the exergetic analysis is a suitable method for the overall optimizing of energy systems. It is found that both an optimization of the supply temperature in thermal networks as well as the appropriate selection of supply units is ensured. It can be concluded, that the exergetic analysis highlights the importance and necessity of demand-adapted supply.

7.1.4 Evaluation of existing buildings (scenario C3)

As part of scenario 3, the potentials of renewable-based district heating supply for the German building stock is evaluated. As already mentioned in chapter 6, the supply temperature for all variants is chosen to be 75 °C to ensure security of supply.

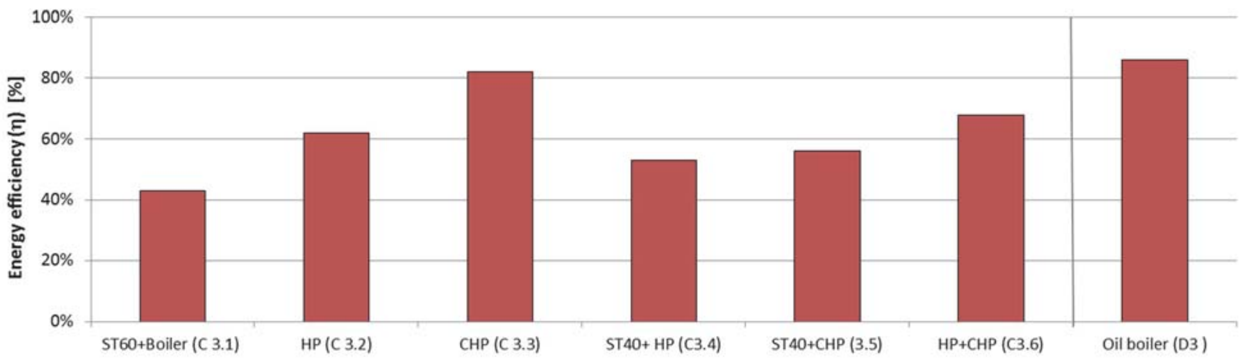


Figure 7-7: Energetic evaluation of centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

According to Figure 7-7 the decentralised "Oil Boiler (D3)" shows the highest advantages in case of energy efficiency (86 %). In contrast, "ST60 + Boiler (C 3.1)" is not advantageous since about one third of the absorbed energy cannot be used which results in high thermal losses. In case of the renewable-based supply options, also the monovalent "HP (C3.2)" and the combined variant

"HP+CHP (C3.6)" result in good energy efficiency (62 - 68 %) due to a good SFP of almost 4. In case of the decentralised supply variants "CHP (C3.3)" achieves the highest energy efficiency of 82 %. The energy efficiency of the variants, where solar thermal (ST) collectors are combined with the GSHP or the CHP, decreases by the influence of the ST are compared to the monovalent variants (53 - 68 %).

Compared to the new construction variant C1 the efficiency of the monovalent heat pumps (HP (C3.2)) drops by approximately 8 % due to SPF of 3.8. In contrast the energy efficiency of the CHP is only reduced by 1%. This result is attributable to the use of natural gas, which has high energy content. The comparison of the scenarios C1 and C2 shows that the energy efficiency of the supply variants using solar thermal energy is up to 16 % lower. This is attributable to the higher supply temperatures (ΔT = 30 °C) and the less efficient buildings which result in high thermal losses.

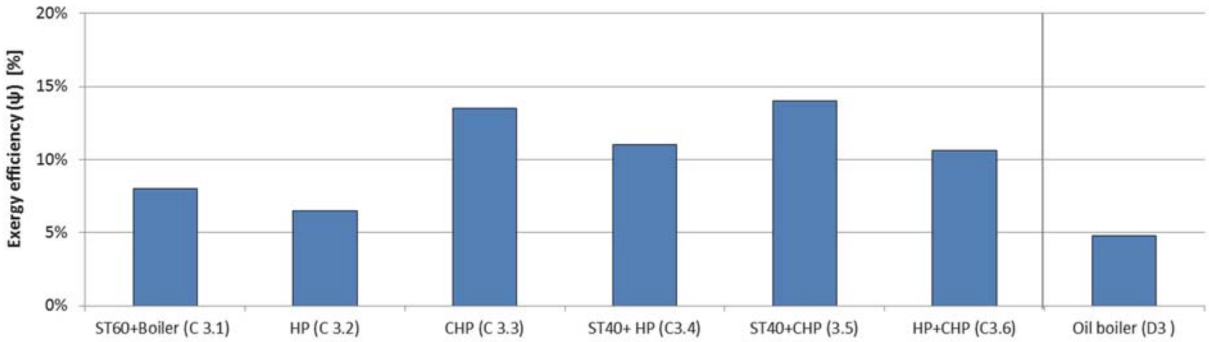


Figure 7-8: Exergetic evaluation of centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

Like in case of the new buildings the results of exergy assessment are almost complementary. From exergy point of view the oil boiler (D3 – reference) has a very low efficiency of less than 5 %. This is even 1.5 % lower than the NG boilers in the new buildings. In contrast the scenarios "CHP (C 3.3)" and "ST40+CHP (C 3.5)" are the most suitable solutions wherein the efficiency of "ST40+CHP (3.5) is slightly higher. The comparison with the corresponding supply scenarios of the new clusters shows that the exergy efficiency for the existing clusters drops between 3 - 5 %.

The supply scenarios using a heat pump are less advantageous in comparison to the corresponding variants of the new buildings. The result corresponds to the outcome of chapter 7.1.3, where a rise in temperature leads to a reduction in the exergy efficiency. Even if the demand of (high quality) electricity of the heating rods significant reduced, the compressors of the heat pumps require more compressor power to produce a supply temperature of 75 °C. Nevertheless, the exergy efficiencies are slightly higher, as the energy demand of the existing buildings is higher.

From the results of the evaluation of the building stock (C3) it can be concluded that the renewable based supply is possible and exergy promotes renewable-based supply also for existing buildings.

The overall evaluation of the technology comparison clearly shows that the exergy assessment promotes district heating supply based on renewable energy sources and energy assessment energetic analysis helps to identify losses. For that reason it can be concluded that the exergetic analysis shows optimization potential beyond energy analysis because of demand-adapted supply. Hence the energetic and exergetic analyses should always be combined. Nevertheless no quantitative conclusions can be drawn on maximizing the use of renewables or minimizing emissions. For that reason the evaluation of GHG by CO_2 as an indicator for global warming potential (GWP) is discussed as part of next chapter.

7.2 Greenhouse gas (GHG) emissions

As part of this chapter it is evaluated which greenhouse gas emissions (GHG emissions) are caused by which technology used in the system. Furthermore it is analysed which proportional relationship exists between of GHG emissions and exergy efficiency.

The total carbon dioxide equivalents (CDE) of the scenarios are evaluated by using stack graphs (GEMIS 2016). For the evaluation two figures are used. The first figure includes all emissions caused by the corresponding energy supplier. The second figure includes the total GHG emission, including the reductions by the electricity generation of the CHP.

7.2.1 Evaluation of supply for new buildings (scenario C1)

The evaluation of GHG emission of the centralised supply (scenarios C1) and decentralised scenarios (NG Boiler D1) as well as (HP D2) for new buildings is shown in Figure 7-9. Basically the "HP (D2)" causes the highest amount of GHG-emission in comparison to all variants. In comparison to the NG boiler, the GHG emissions of the decentralised "HP (D2)" are increasing by 20 %. This is mainly because of the different CO_2 equivalents (CDE) of the investigated energy carriers (see also Table 5-1 in chapter 5.2).

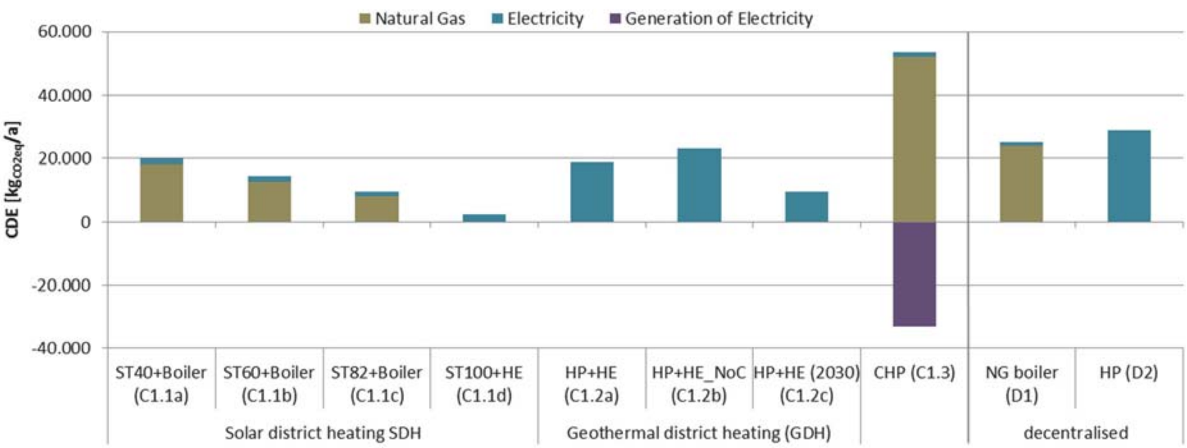


Figure 7-9: GHG emissions of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

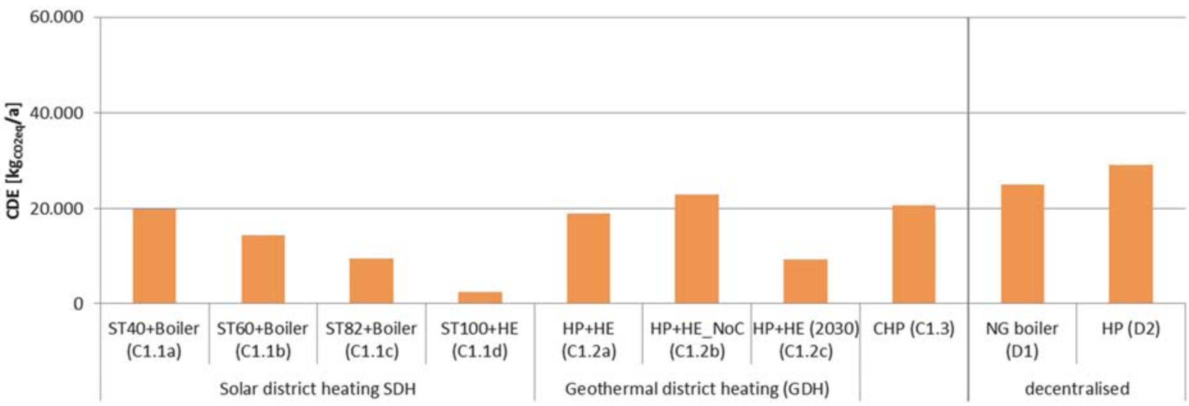


Figure 7-10: Total GHG emission of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

The overall evaluation of the SDH scenarios shows that an increasing degree of solar coverage from 40 % to 100 % results in a significant reduction of greenhouse emissions of about 90 %.

The highest potential for significant reduction of GHG emissions is drawn by scenario "ST100+HE (C1.1.d)". In this variant the GHG emissions are solely caused by the electrical heaters, which are mainly used for providing heat during heating season and for production of PWH. In relation to the centralised HP the GHG emissions of the decentralised heat pump are higher (42 %). In the case of individual building supply, a higher demand for electricity (compressor power and pumping power) is necessary due to the preparation of potable water hot. A possible improvement of the system could be achieved if the heat pump is operated with a solar thermal system.

The comparison of "HP+ HE (C1.2a)" and "HP+HE_NoC (C1.2b)" shows that the GHG are slightly rising due to the increased use of heating rods and the higher compressor demand to re-heating the thermal grid at the beginning of the heating period and thus more electrical energy is required. Furthermore, the positive influence of the rising share of renewable energy in the electricity mix is observed in "HP+HE (2030) (C1.2c)". However it should be noted critically that this approach allows the comparison with other scenarios only to a limited extent. Nevertheless potential benefits of the heat pump are shown when the share of renewable energies in the electricity mix increases (see also discussion in section 7.1.1). The comparison of the "HP+HE (C1.1d)" to the CHP "CHP (C1.3)" shows that the GHG emission of the CHP are slightly lower, even though a larger amount of fuels is necessary (Figure 7-10). The production of electricity is mainly responsible for this effect (see Figure 7-9), which has a positive impact on the overall balance.

As already shown in the course of the exergetic analysis, a higher share of renewables (solar thermal energy and increasing share of RES in the electricity mix) has a positive impact and an increasing use of fossil fuels has a negative impact on the overall balance. The direct, exemplary comparison shows that the increase from 40 % solar fraction to 100 % solar fraction leads to a 120 % increase in exergetic efficiency and a 90 % reduction in GHG emissions. However in addition, the quantification of the savings of GHG emissions (credit) of the CHP unit is only possible to a limited extent due to the definition of the overall exergetic efficiency.

7.2.2 Evaluation of multi-generation for new buildings (scenario C2)

The evaluation of the geo-solar district heating (GSDH) variants shows that the GHG emissions are decreasing with a higher amount of usage of solar thermal energy.

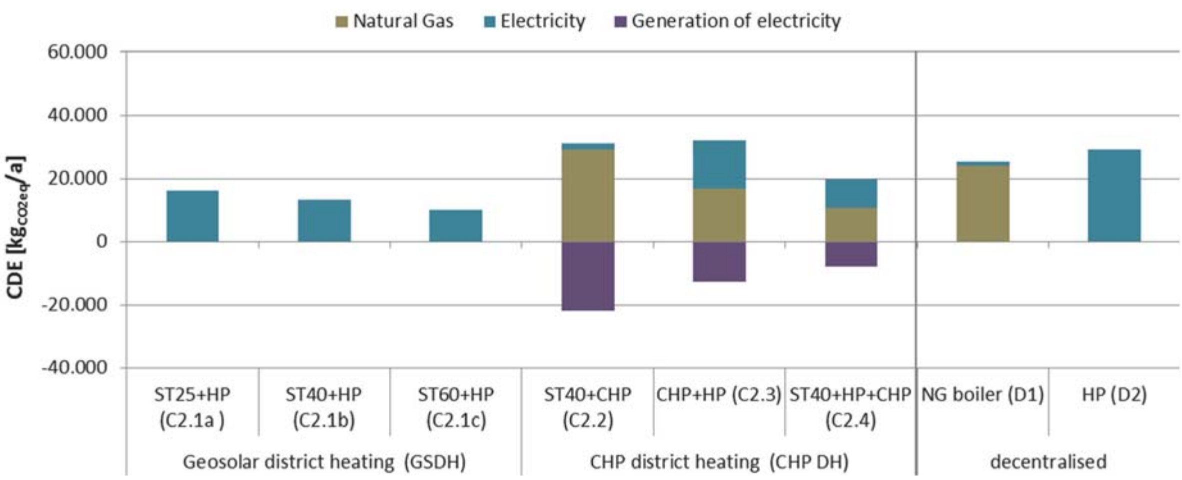


Figure 7-11: GHG emissions of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

The overall comparison of C1 and C2 shows that the combination of different renewable energy suppliers is advantageous, since a significant overall GHG reduction of approximately 23 % can be achieved. Like shown in the case of the scenarios C1 an increasing share of solar thermal energy leads to a reduction of GHG emissions. In addition, the generation of electricity in case of the CHP units has a positive impact on the overall balance.

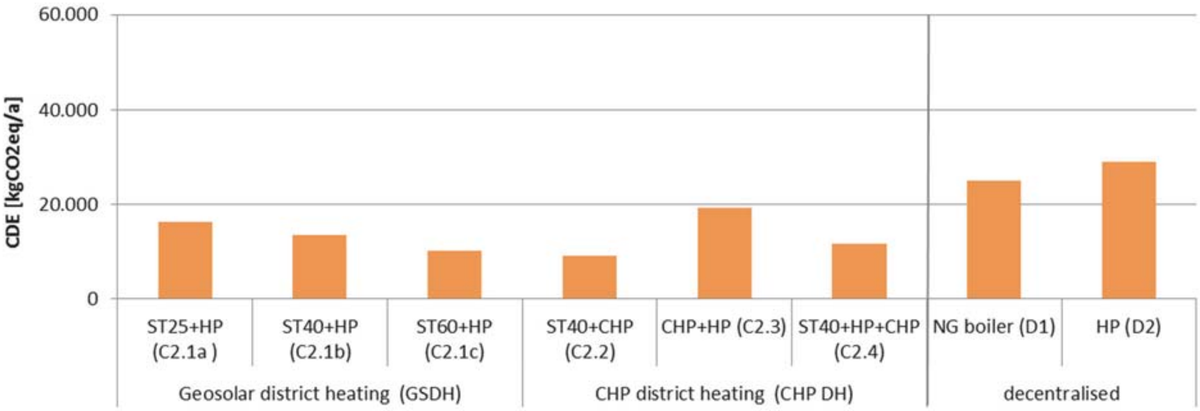


Figure 7-12: Total GHG emission of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

Furthermore it can be concluded that the exergetic evaluation and the analysis of the total CDE show comparable results with the same tendencies for increased use of renewable energy. An estimation of amount of saving potential of the CDE can only be inferred insufficiently from the exergetic analysis.

7.2.3 Variation of supply temperature for new buildings

As mentioned in chapter 6.2, the temperature level for selected scenarios is increased gradually from 45 °C to 75 °C. Like shown in previous chapters, the comparison of “ST40 + HP (C2.1b)” and “ST60 + HP (C2.1c)” shows that the higher solar coverage rate has a positive influence on the greenhouse gas balance. Next to this the evaluation demonstrates that the amount of GHG emissions in scenarios “ST40+HP” and “ST60+HP” rise by double or triple in total, as the electricity demand for compressor of the heat pumps increase. In contrast the amount of GHG emissions in “ST100+HE (C1.1d)” decreases slightly of about 13 % in total since the use of the heating rods decreases (see also chapter B4 in the Appendix B).

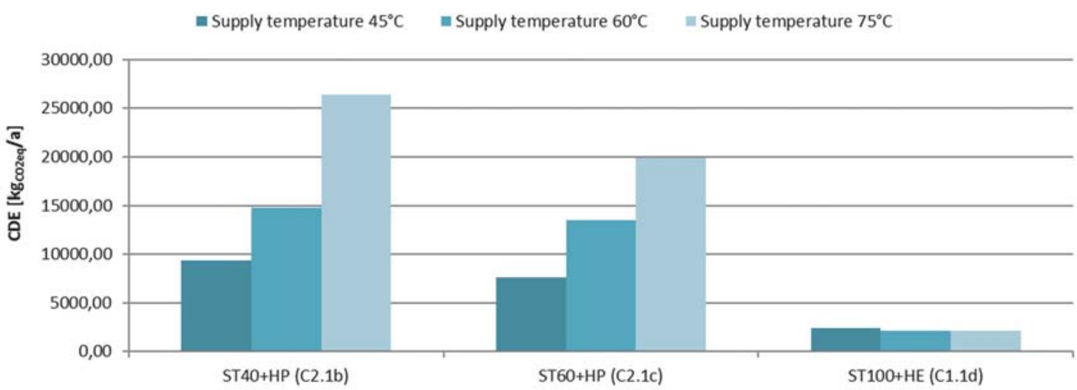


Figure 7-13: Assessment the influence of rising supply temperatures on the CDE for selected supply scenarios.

The comparison of the results of the analysis of the GHG emission and the exergy efficiency (see Figure 7-6) shows a good but antiproportional agreement of the results. In a direct quantitative comparison, it is shown that the effect of the exergetic analysis is slightly less pronounced.

7.2.4 Evaluation of existing buildings (scenario C3)

As part of scenario 3, the potentials of renewable-based district heating supply for the German building stock is evaluated. As reference technology, an oil boiler is used. The highest GHG emissions are caused by the "Oil Boiler (D3)". These are attributable to the high energy carrier requirement together with the high CDE output of heating oil. In the case of the monovalent variants "HP (C3.3)" and "CHP (C3.2)", both systems are approximately the same. The high emissions of the CHP (methane) are significantly reduced by the credit from the electricity production. Compared to the monovalent variants, the two solar-supported scenarios "ST40+HP (C3.4)" and "ST40+CHP (C3.5)" show slight reductions of the GHG emissions. The combination variant "HP+CHP (C3.6)" on the other hand, has no advantages compared to the monovalent variants.

The comparison of the new and the existing building cluster shows that the GHG emissions are up to two times higher for the supply of existing buildings.

The analysis of the CDE further shows that in contrast to exergetic analysis, the amount of potentially avoidable CO_2 emissions becomes visible, since the simulated demand of the fuels are assessed from a quantitative point of view. Even if the exergy utilization is correlated with a decrease in CO_2 emissions (Hertle et al. 2014; Dincer, Rosen 2013), no direct, numerical statements[21] can be made about the quantity of GHG emissions.

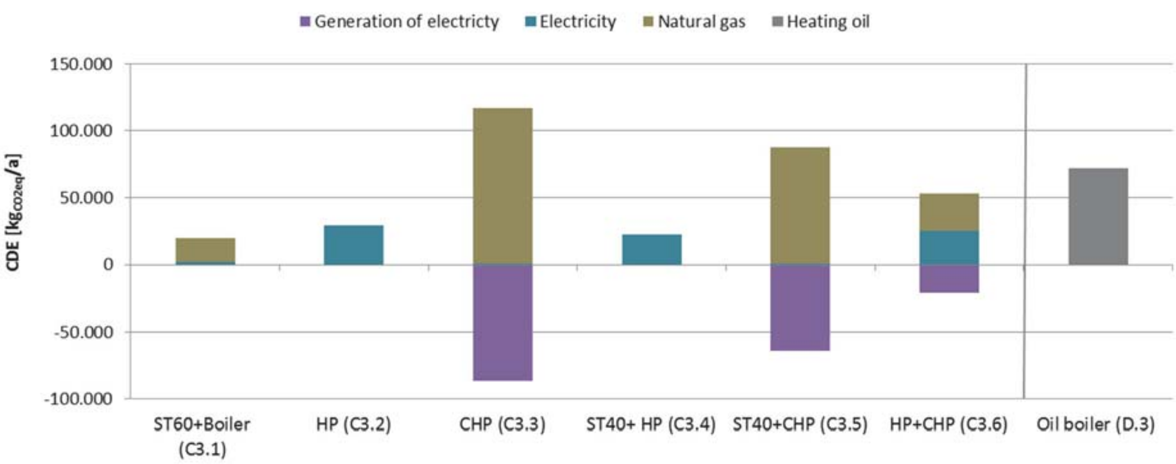


Figure 7-14: GHG emission for centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

Figure 7-15: Total GHG emission centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

[21] It should be noted that several factors and correlations are available which are directly linking the exergy with environmental influences and sustainability. An overview could e.g. be found in Dincer, Rosen 2013.

Starting from the results shown, it becomes clear that the exergetic analysis and the analysis of GHG emission show almost proportional results. Nevertheless it is also concluded that the meaningfulness of the results was increased by the combination of exergy and energy assessment as well as the assessment of CO_2 emissions.

Another important factor for the evaluation of small scale district heating supply is the consideration of economic aspects. For this reason the assessment is expanded by estimation of economy.

7.3 Economy (full cost calculation according to VDI 2067)

As part of the economic feasibility studies, according to (VDI 2067 2012), the specific heat price is used for comparison of the different supply scenarios. For the evaluation in the first step, the annuity of the annual heat demand of each scenario is estimated. The annual costs consist of the capital-linked costs, the capital-related costs, the operating costs (fuel and maintenance) and the proceeds (calculated revenues). It is assumed that no other costs are incurred. If proceeds are generated, the costs are reduced accordingly. The annuities of the annual costs are converted into heat prices by dividing the annuities by the annual heat demand.

7.3.1 Evaluation of supply for new buildings (scenario C1)

The evaluation of the specific annual costs shows that the decentralised energy suppliers, NG boiler (0.15 €/kWh) and decentralised heat pumps (0.21 €/kWh), are causing the lowest annual costs. Since also here, the cost of the PWH production are evident, it is expected that the energy costs decrease if the centralised heat pumps are supported by a solar system (Schmidt et al. 2014).

In case of the centralised supply variants, the costs for the heating network influence the overall costs of these variants. The costs for all variants are quantified to be 0.09 €/kWh. The evaluation shows further that the solar districts heating (SDH) have the highest specific heat price. This comparatively high price is attributable to the investment costs (capital-linked costs), the investment costs for the seasonal storage and the collectors. In case where the solar coverage is raised from 40 % (ST40+Boiler (C1.1a)) to 82 % (ST82+Boiler (C1.1c)), the capital costs also rise by approximately 32 % (Figure 7-16). At the same time, the consumption costs for the peak load boiler are reduced. Nevertheless, a decline in consumption costs cannot reduce the linked capital costs, since the operation related costs increase at the same time (Figure 7-17). As part of the solar district heating the scenario “ST 100 + HE (C1.1d)” has the highest specific heat price. In this variant, the capital-linked costs are the highest.

The evaluation of the geothermal district heating shows that the heat price of the centralised heat pumps (D2) is higher in comparison to the decentralised variants (C1.2). This is mainly due to the investment costs of the heating grid. In contrast the operational related cost are higher due to high compressor output. The overall comparison of the GDH variants shows that the deactivation of circulation in summer “HP_NoC (C1.2b)” leads to slightly higher consumption related costs due to an increased use of the heating element (PWH). As a result the specific heat price increases slightly. Furthermore the heat pump “HP 20230 (C1.1c)” shows increasing consumption costs. This is explained by expected increased electricity prices in 2030 compared to the reference year (2015). In comparison to the GDH a similar price level is shown for centralised heat pumps scenarios even through a higher amount of fuel is required. But the comparison of the cost groups (Figure 7-17) clarifies that this is explained by the lower operating costs due to the use of heat from the environment (geothermal heat) for the HP.

In contrast the CHP has higher operating costs but the consumption related costs are reduced since proceeds are generated by production of electricity.

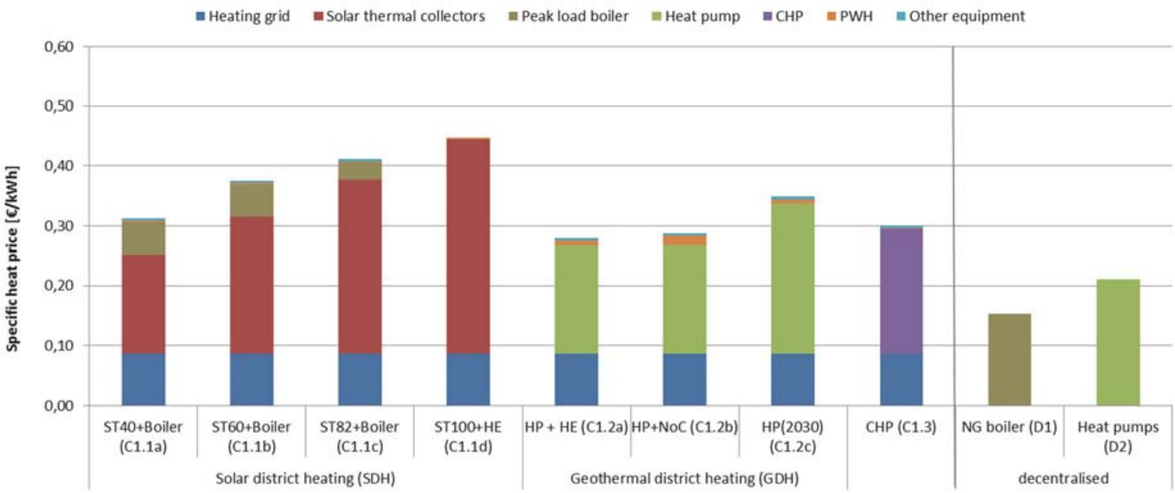


Figure 7-16: Economic evaluation (specific heat price) of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

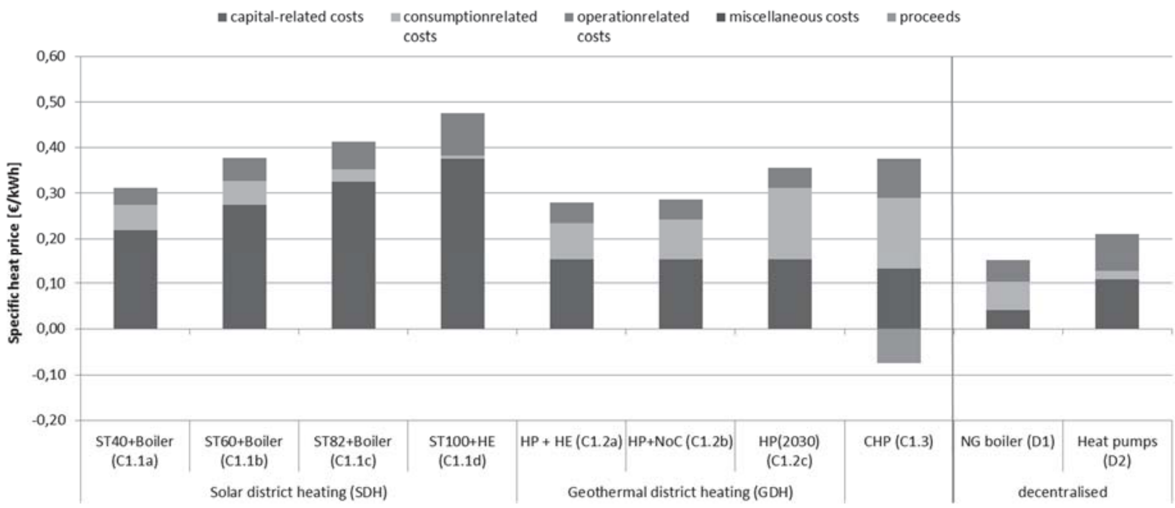


Figure 7-17: Overview of cost groups of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

According to the results, and as expected, a higher share of solar thermal energy and the alternative heat pump configurations show rather disadvantages to reduce the costs.

7.3.2 Evaluation of multi-generation for new buildings (scenario C2)

As already seen in evaluation of scenario C2, the decentralised energy suppliers are causing the lowest annual cost and differ from the specific heat price of different energy sources. Also here the cost for the heating network is quantified to be 0.09 €/kWh.

The evaluation of the geo-solar district heating (GSDH) variants shows, that the specific heat price increases with higher solar fraction. In contrast to the SDH variants additional costs are occurring due to a necessity of a geothermal field. Like in the SDH scenarios (C1.1), the consumptions costs are reduced. Althought the consumption costs decline, the capital costs are not reduced. In relation to the corresponding SDH scenarios the specific heat price of the GSDH increases of 0.12 €/kWh mainly due to the capital related cost. The comparison of the corresponding scenarios of the solar district heating and geo-solar district heating clarifies that if the solar collectors are combined with a CHP instead of a GSHP the heat price rises about 0.02 €/kWh.

In case of CHP DH it is shown that the proceeds of the generated electricity has an overall influence on the specific heat price (Figure 7-19). If this is taken into account, the combinations of the CHP and the centralised heat pump (C2.3) achieve the greatest advantages. But the overall comparison demonstrates that the combination of different energy suppliers is generally rather disadvantageous.

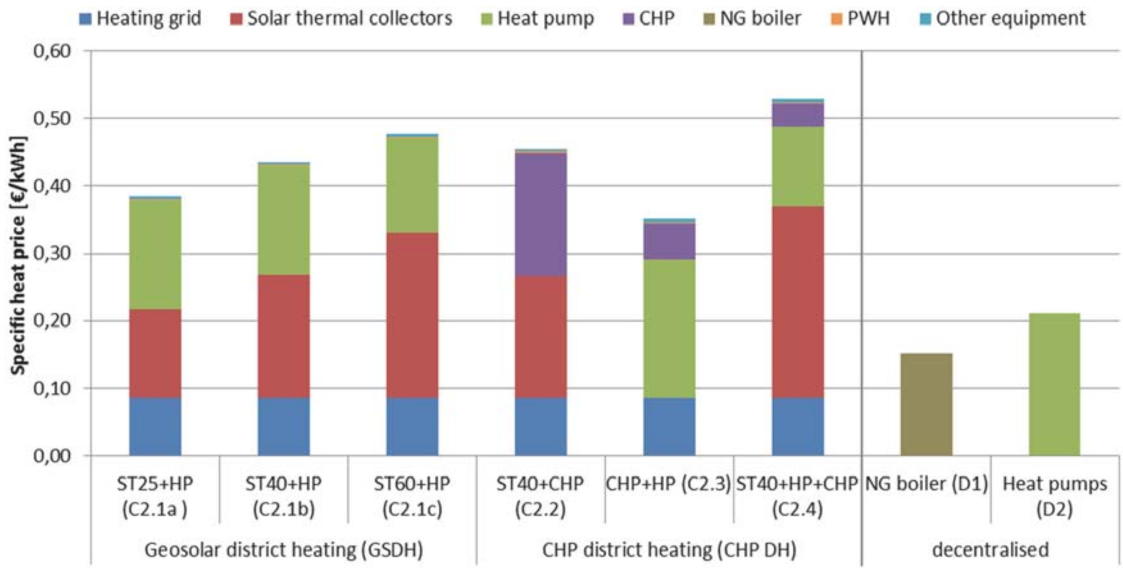


Figure 7-18: Economic evaluation (specific heat price) of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

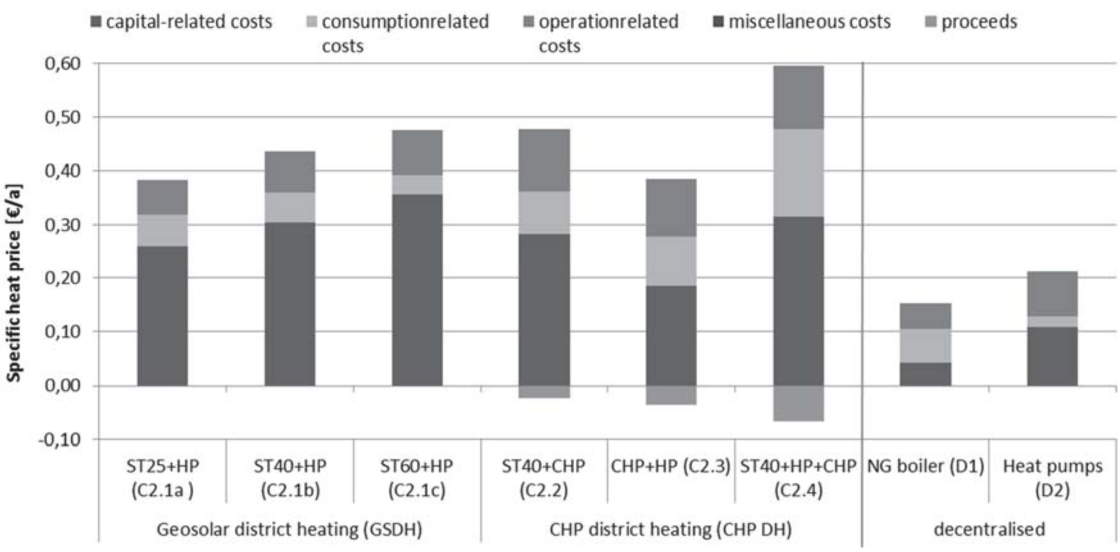


Figure 7-19: Overview of cost groups of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

In case of the scenarios C1 and C2 the results are compared to values found in literature (e.g. (Schmidt et al. 2014)). It can be concluded that the heat price with a larger number of customers is expected to decline and will lead to greater efficiency in case of economic issues. Thus, the size but also the location of the supply area (solar radiation and ground heat) has a great influence on the economy.

7.3.3 Variation of supply temperature for new buildings

As mentioned in chapter 6.2, the temperature level for selected scenarios is increased gradually in 15 °C steps; from 45 °C to 75 °C. The evaluation shows that the consumption but also the operation related cost decrease, due to the rising temperature level. This is related to the decreased use of the heating rods. The evaluation graph of the specific heat price of the cost groups is not shown here, since the same conclusions can be derived from the representation of the evaluation of the system components.

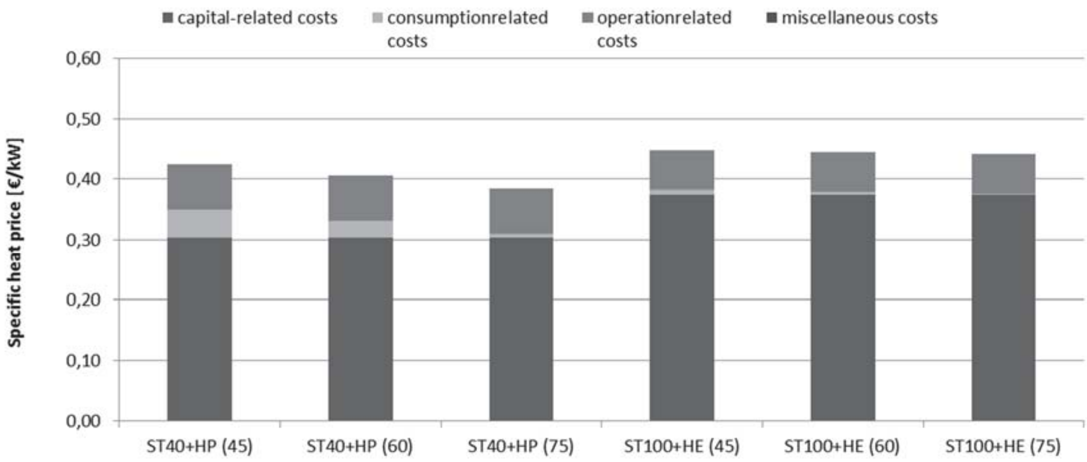


Figure 7-20: Change of heat price regarding temperature variation for selected supply scenarios (reference T_{supply}=45 °C).

Next to this, this scenario further demonstrates the necessity of the combination of exergy evaluation and evaluation of costs.

7.3.4 Evaluation of existing buildings (scenario C3)

The reference variant „Oil boiler (D3)" shows the lowest overall heat price. This is because there is no heating network regarded in this variant and the investment costs for the heating system are low in comparison.

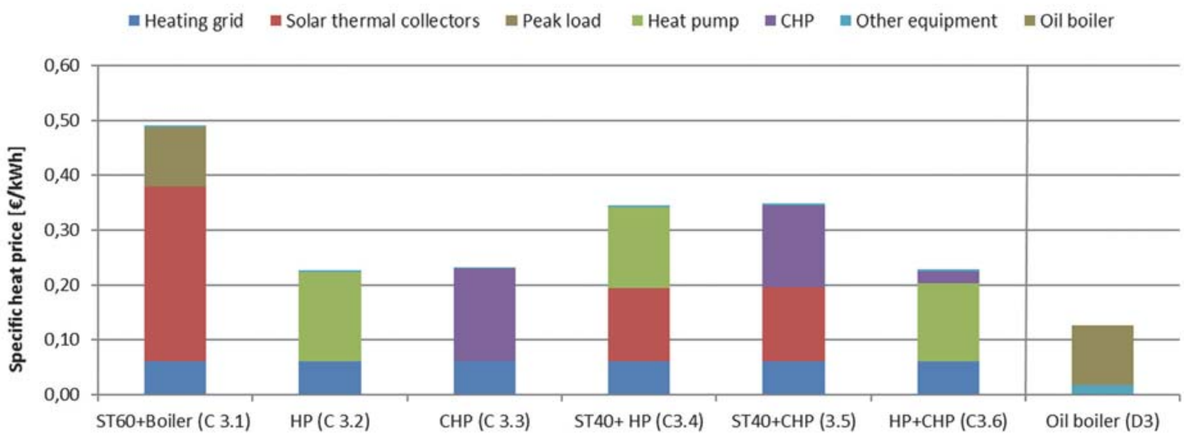


Figure 7-21: Specific heat price of centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

Compared to all decentralized variants, the "ST60 + Boiler (C3.1)" has the highest heat price, which is mainly caused by capital-linked costs. This is due to the unconventional design with a solar coverage of 60 %, which results in a significant over-dimensioning and necessitates seasonal storage. This result in high investment costs, which however cannot be compensated by the higher solar yields. The heat prices of "HP (C3.2)" and "CHP (C3.3)" are significantly lower (0.27 €/kWh) than the heat price for "ST60 + boiler (C3.)". Despite the higher investment costs of GSHP, both suppliers are almost equal.

When looking at the cost groups (Figure 7-22), this is explained by the significantly lower operating costs due to the use of environmental heat of the HP. The CHP also has higher operating costs. These additional costs are compensated by the proceeds of the electricity production. The "ST40 + HP (C3.4)" and "ST40 + CHP (C 3.5)" have slightly lower costs for the main suppliers due to the reduced cost caused by the usage of solar thermal energy. However, these savings do not cover the additional costs of ST plants, which make the solar-supported variants more expensive. The combination variant "HP + CHP (C3.6)" is clearly below the monovalent variants "HP (C3.2)" and "CHP (C 3.3)". In this variant, the CHP is significantly longer in operation than in the monovalent case. The basic load is covered by the CHP and the peak load is covered by the GSHP. Because of the resulting proceeds of the CHP the variant "HP + CHP (C3.6)" results in a significant improvement of cost efficiency in comparison to the monovalent variants.

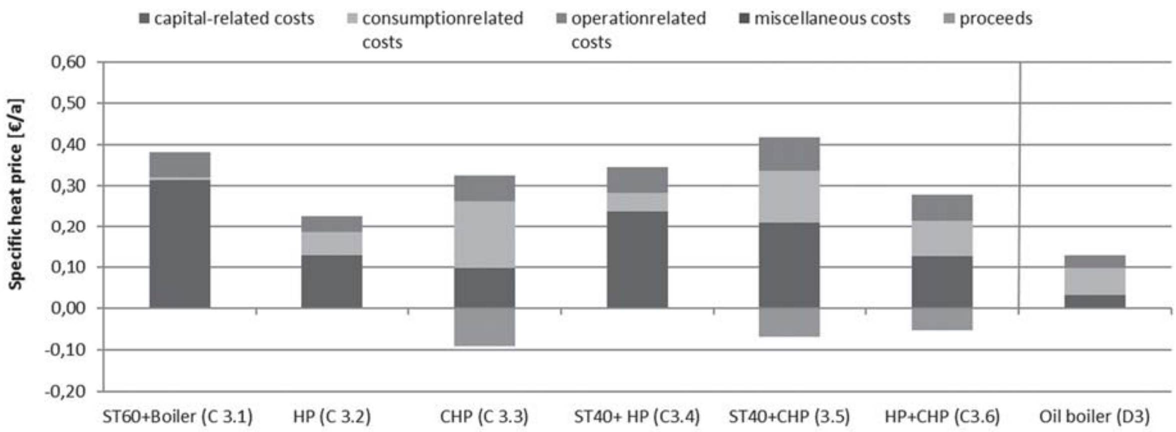


Figure 7-22: Overview of cost groups of centralised (scenarios C3) and decentralised (D2) supply for existing buildings.

The economic analysis carried out here can only provide a tendency for the performance of a variant. In the case of the consideration of a larger network, a clear improvement in profitability is to be expected. As the evaluation of all scenarios clearly shows, the capital-bound costs make up a large part of the total costs. The regressive trend of investment costs shows that larger plant sizes will lead to lower specific costs. This scale effect can give decisive advantages. The heat prices for the decentralized variants are not affected by the scale effects. Furthermore, no financial subsidies for ST, HP and CHP were taken into account. A further improvement in profitability depending on the investigated supply area is therefore very likely. Likewise, the solar radiation and the geothermal heat are dependent on location and also have a great influence on the economy.

7.4 Soft Evaluation Factors (SEF)

As already mentioned as part of chapter 5.4, two Soft Evaluation Factors (SEF) "Demand of space (area): Weighted Area Units (WAU)" (see chapter 5.4.1) and "Flexibility potentials" (see chapter 5.4.2) are defined and added to the assessment. Both factors can only be quantified on an approximate basis and do not replace any detailed planning of urban spaces or the potential analysis of energy sources.

7.4.1 Quantification of the required installation area (weighted area units)

In this section the consideration of the area utilization or area requirements of the individual supply components is investigated. Since the data does not reflect the actual plant sizes, the so-called "Weighted Area Units" (WAU) are used.

Figure 7-23 shows the WAU of the monovalent scenarios for new buildings. The comparison of the centralised supply (scenarios C1) and decentralised scenarios (NG Boiler D1) and (HP D2) for new buildings shows, that the decentralised scenarios have the lowest demand of space. Particularly in the case of the NG boiler, the gas network has an effect on the evaluation. The space requirement for the heat probe field in D2 is larger in comparison to the decentralized variants of the GSDH, since a higher number of probes is necessary.

The overall comparison of the solar district heating variants leads to the conclusion that "ST100+HE (C1.1d)" has the highest demand of space with regard to WAU, because of the required space for solar field (solar collectors). Furthermore the space demand for the seasonal storage increases slightly with increasing collector area.

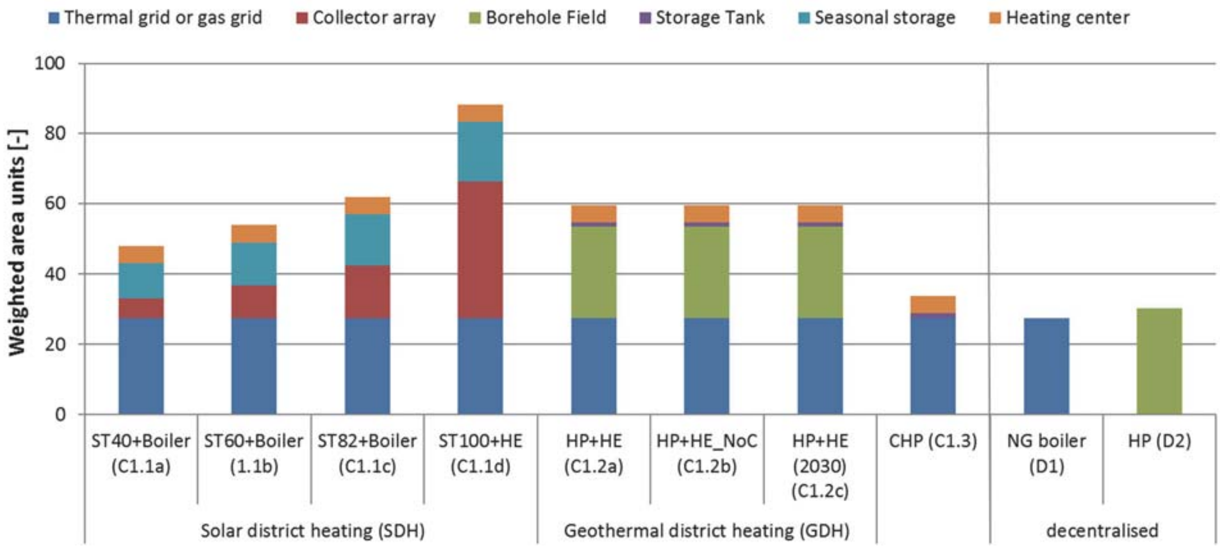


Figure 7-23: WAU of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

The space requirement for the geothermal district heating scenarios is almost the same as the number of heat probes does not change in this variant. In comparison to all decentralised variants, the "CHP (C1.3)" has the lowest space requirement, since neither solar collectors nor geothermal probes are used. Nevertheless, additionally space for a gas network is required, which serves the direct supply of the CHP. The gas grid is not embedded together with the heating network, but is connected directly to the local gas network of e.g. the surrounding city.

Also in the case of multivalent supply (Figure 7-24) the comparison of the geo-solar (C2.1) and CHP district heating (C2.2-C2.4) to the centralised scenarios (D1 and D2) indicates that the reference scenarios have the lowest demand of space, since no collectors are used in this variant.

In case of the geo-solar district heating scenarios (GSDH) the variant "ST60+HP (C2.1d)" has the highest demand of space because of the required space for solar collectors. The comparison of all geo-solar supply variants shows that the space increases with increasing solar coverage rate due to the required space for the collectors and the increasing volume of the seasonal storages. The space requirement of the geothermal probes for all geo-solar variants remains almost the same as the number of heat probes does not change. The space demand for the CHP district heating variants is lower in comparison to the geo-solar supply variants since no thermal collectors are required respectively the number of BHE decrease because of using solar thermal collectors. “CHP+HP (C2.3)” shows the lowest WAU, since no solar collectors are used. The comparison of the multivalent scenarios and the monovalent scenarios demonstrates that the combination of different energy suppliers is rather disadvantageous.

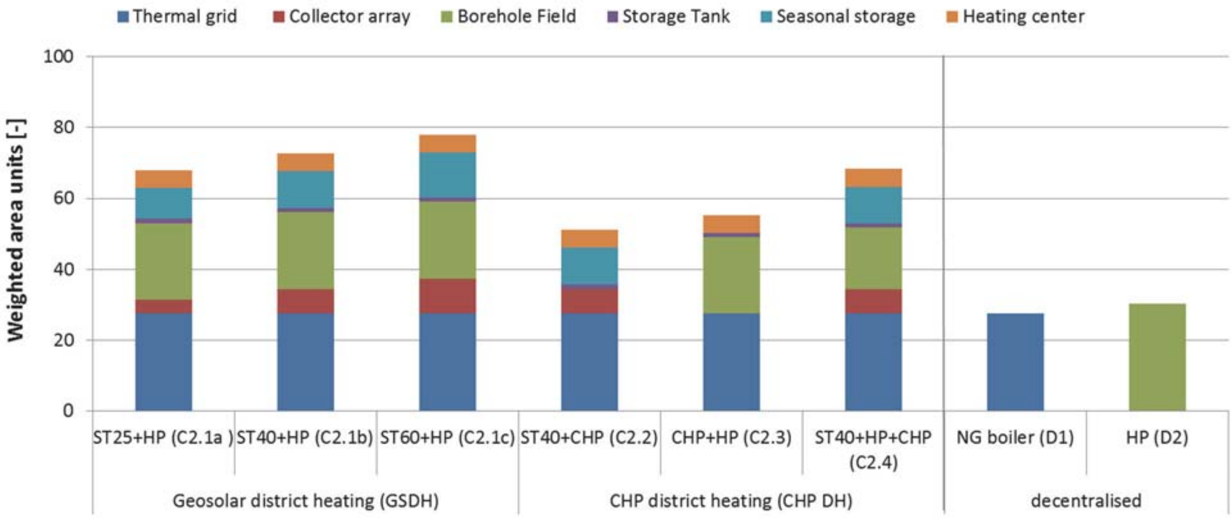


Figure 7-24: WAU of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

The comparison of the centralised supply (scenarios C3) and reference scenarios (oil Boiler D3) for existing buildings shows that in case of the centralised variants the “ST+boiler (C3.1)” results in a high number of weighted area units. The high space requirement for the collector field and seasonal storage are responsible for this result.

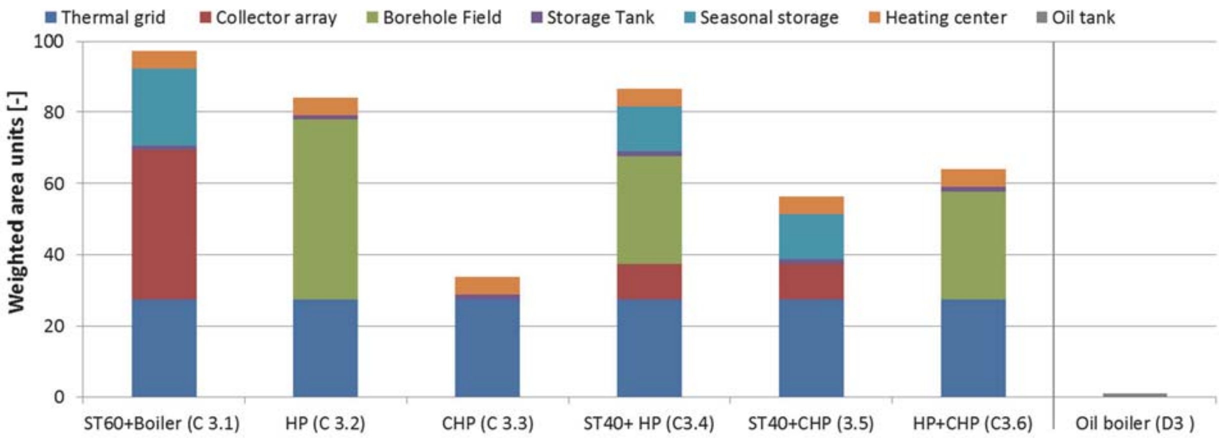


Figure 7-25: WAU of centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

Next to this, the variants “HP (C3.2)” and “ST+HP (C3.4)” have comparatively high space requirement because of the large area requirement of the geothermal field. In "ST40 + HP (C3.2)" this is due to the requirements of the geothermal field and the solar components. In comparison to “CHP (C3.3)” the CHP scenarios combined with one more energy source (“ST40+CHP (C3.5)” and “HP+CHP (C3.6)” have a higher number of WAU. The reference variant shows the smallest space requirement. In case of almost all scenarios of the existing building cluster the WAU is higher with regard to the cluster of new buildings. In particular, the areas of solar thermal collectors and the number of geothermal probes increase very strongly with increasing demand for power for the producer units.

7.4.2 Flexibility potentials for using increased share of fluctuating RES

In case of flexibility potentials the expected advantages regarding increasing share of fluctuating renewable energies (RES) in the future electricity mix is assessed (see also discussion in chapter 5.4.2). The evaluation is based on own, qualitative assumptions based on a short literature research (e.g. (Huenges et al. 2014; Sperber, Viebahn 2013)), for that reason the factor is a soft evaluation parameter. For comparison the different scenarios are ranked by using percent values. The main evaluation parameters are the size of the storage (volume) and the "grid supportivity" respectively the "market supportivity" (BDEW 2015b) of the regarded energy supplier. In case of all centralised variants it is assumed that the heating grid has a positive effect on the flexibility, since the storage units connected to the suppliers can directly be used to supply the buildings.

Figure 7-26 shows the estimated flexibility potential for the cluster of new buildings (C1). The variants of the SDH concepts are evaluated with low flexibility potential since energy suppliers are not implemented which are able to react directly to the increasing supply of fluctuating renewable electricity. Nevertheless, with a higher solar coverage rate, also the volume of the storage increases. It is assumed that the higher the available volume the higher the potential for flexibility. In comparison, the variant "ST100 + HE (C1.1d)" shows great potential for flexibility. Since this variant has a large storage volume and heating rods are used for heating.

In comparison to the SDH scenarios, the geothermal district heating (GDH) variants have a high potential. Particularly in the case of a high share of excess electricity, these heat pumps can be used for charging the storage units. In comparison to "ST100 + HE (C1.1d)", the potential of "HP+HE (C1.2)" is estimated to be slightly lower, since the storage volume is smaller. The potential of the flexibilization decreases, if the circulation is switched off in the summer (HP+HE_NoC (C1.2b)), since the heat pumps are not available during that time. The variant "CHP (C1.3)" shows potential regarding market supportivity. In times with low incidence of PV or wind power, the electricity produced can be used for additional capacities or sold. In the case of the decentralised variants only the heat pumps shows advantages. In comparison to the centralised HP the flexibility of the centralised HP "HP (D2)" is estimated to be slightly lower, the storage capacity is low and the thermal network is missing. In case of the NG boiler only the implemented heating rod shows small advantages with regard to the grid flexibility.

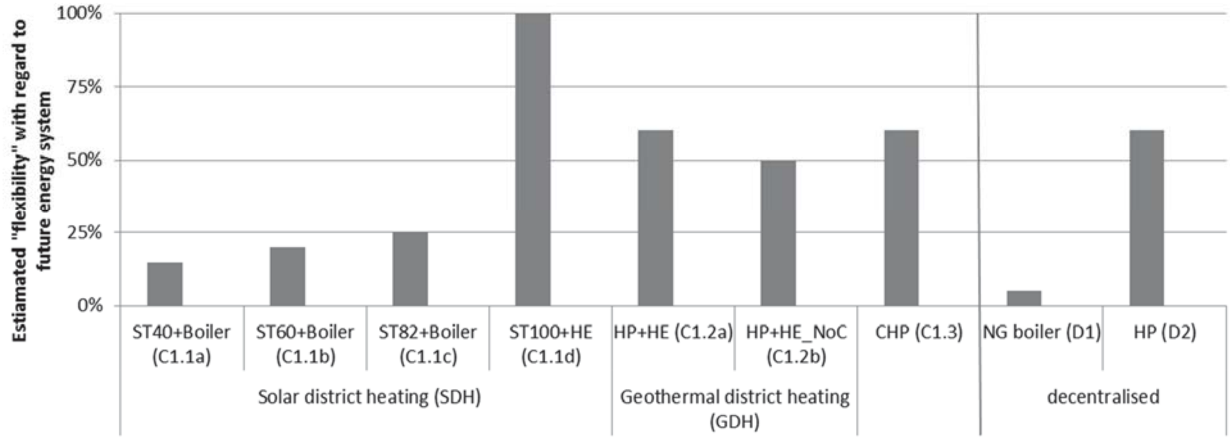


Figure 7-26: Estimated flexibility potential of centralised (scenarios C1) and decentralised (D1 and D2) supply for new buildings.

In comparison to the SDH concepts it is assumed, that the potential of flexibility increases if heat pumps (geosolar district heating) are used instead of peak load boilers. Also here the increasing storage volume has a positive effect on the flexibility potential. The flexibility of "ST40+CHP (C2.2)" is assumed to be equal to "ST40+HP (C2.1b)", since the CHP shows the same potential to the marked supportivity as the heat pumps to the grid supportivity. In contrast the combination of heat pump and CHP unit "CHP+HP (C2.3)" shows potentials regarding both "grid supportivity" and "market supportivity". Since a larger storage device is not implemented in the scenario it is ranked equal to "ST40+HP (C2.2)" and "ST40+CHP (C2.3)". It is assumed that "ST40+HP+CH (C2.4)" shows the highest potential with regard to flexibility.

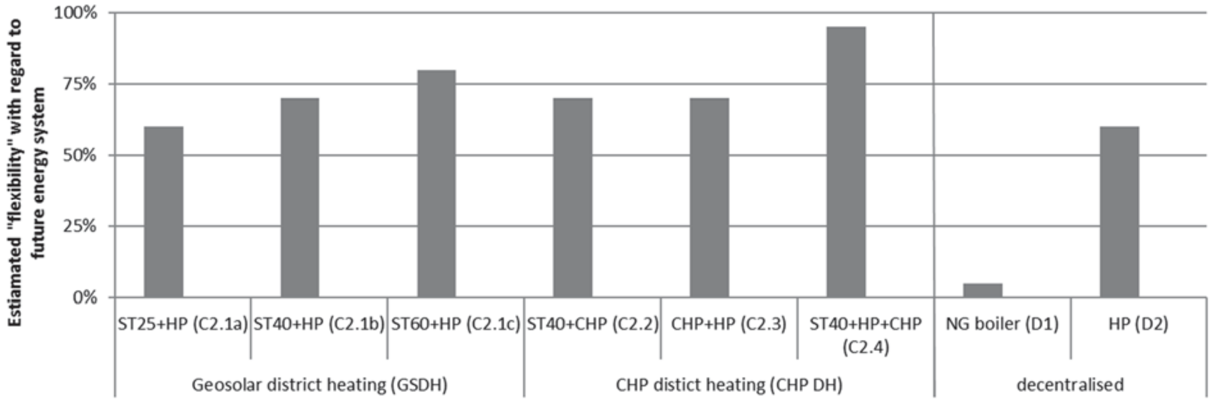


Figure 7-27: Estimated flexibility potential of centralised (scenarios C2) and decentralised (D1 and D2) supply for new buildings.

As part of scenario C3 the variant "ST60+Boiler (C3.1)" only shows small advantages since a seasonal storage and a heating grid is used. The variants "HP (C3.2)" and "CHP (C3.3)" shows equal results. The variants shows high potentials regarding "grid supportivity" and "market supportivity" but in both cases the storage tank is rather small in comparison to the variants using solar thermal collectors. The flexibility of "ST40+HP (C3.4)" is assumed to be equal to "ST40+CHP (C3.5)", since the CHP shows the same potential to the marked supportivity as the heat pumps to the grid supportivity. In both cases a seasonal storage in implemented. In case of the oil boiler only the implemented heating rod shows some small advantages with regard to the grid flexibility.

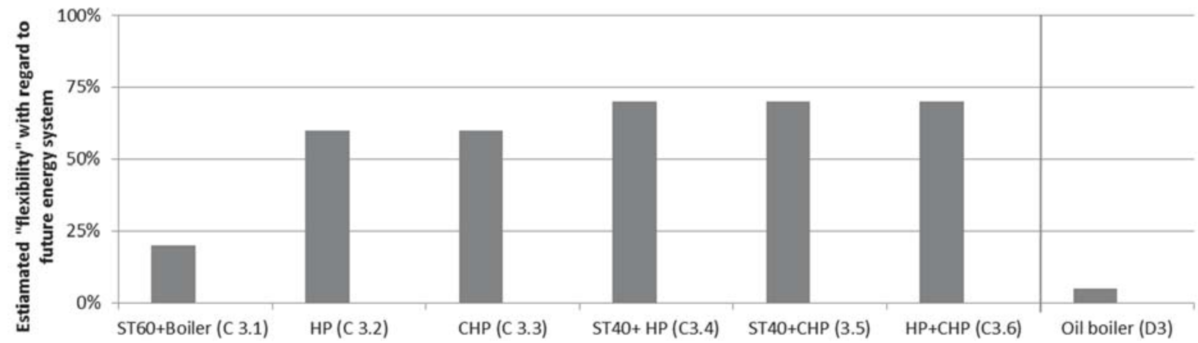


Figure 7-28: Estimated flexibility potential of centralised (scenarios C3) and decentralised (D3) supply for existing buildings.

7.5 Comprehensive discussion of the results

After a detailed presentation of a whole series of scenarios in previous chapters the main results are summarized and discussed in this section.

In the course of the investigation of a new building cluster (C1 and C2) several centralised and decentralised supply options (generation units) are investigated individually or in combination. Furthermore selected supply parameters are varied. Next to the new buildings a building cluster representing the German building stock (C3) is evaluated.

The evaluation of monovalent supply (C1) shows that the decentralised NG boiler is the best solution in case of energy efficiency due to the overall lowest thermal losses. The decentralized NG boiler is also the best supply solution in terms of investment cost and heat price but also in case of space requirements. The highest exergy efficiency and the lowest GHG emissions are achieved by the central scenarios that use a high proportion of solar energy or where a CHP unit is implemented. The highest potential in flexibility is achieved by a variant using big seasonal storage tanks.

In the course of the scenario C2 the combination of different energy suppliers are studied. The energy assessment shows, that the combination of different supply units does not lead to increasing energy efficiency due to the overall thermal losses in the system. In contrast the suitable combination of different supply units leads to an improvement from exergy point of view due to a significant reduction of high valued energy. A similar picture emerges with regard to evaluation of GHG emissions. The evaluation of economy and the space requirement shows, that the combination of energy suppliers has no advantage since specific heat price and the space demand rise in all cases. In contrast the combination of energy suppliers shows advantages regarding flexibility in future energy systems.

Next to the investigation of different supply technologies, the following supply parameters are varied; the solar fraction, the circulation in the grid during summer, the share of renewables in the energy mixes and the level of the supply temperature. In case of increased solar fraction it is shown that the energy efficiency drops due to increasing thermal loses. In contrast exergy efficiency rises since the use of high quality energy sources are significantly reduced. In case of the GHG emissions a significant reduction is achieved. The opposite effect can be observed in the assessment of economic viability as well as in the space requirement since significant higher specific heat prices as well as significant higher space demand can be expected. In case of flexibility options the use of seasonal storages offers possibilities for storing excess electricity. By using the GDH scenarios (C1.2) the influence of the deactivation of the circulation during summer time and electricity mix are studied. The energy and the exergy analysis show that the deactivation is less advantageous due to slightly increasing losses and the increased power demand for reheating the grid. Also in case of the analysis of the GHG emissions and economic viability the increased use of electricity which results in higher consumptions costs. The deactivation is rather disadvantageous in case of flexibility, because excess energy can be exploited only insufficiently. The deactivation has no influence on the space demand. The increased share of the renewables in the electricity mix shows advantages in energy and exergy efficiency as well as reduction of GHG emissions. Furthermore the analysis highlights that a heat pump has the potential to become a key technology in a future energy system. The electricity mix does not affect the space requirement and was further not evaluated against the background of flexibility. Another important supply parameter is the level of the supply temperature. As part of an analysis the temperature level is raised from 45 °C to 75 °C. It is shown that a rising temperature level leads to increasing losses but also to increasing demand of electricity which has a negative impact on the exergy and energy efficiency. Nevertheless the exergy assessment shows optimisation beyond exergy analysis since the use of electrical energy can be reduced in one case. The increasing temperature level has also negative impact on the GHG emissions but a positive impact in case of the cost evaluation.

As part of scenario C3, the renewable-based supply of the German building stock is studied. The simulation studies already show that the renewable-based supply of existing buildings is possible but at the rather higher supply temperatures of 75 °C. This analysis also shows that the decentralized variant (here: oil boiler) has the best energy efficiency due to the low thermal losses. The use of renewable energy sources leads to a better exergy efficiency and to a reduction of the GHG emissions. However in case of the economic feasibility studies it is shown that the oil boiler is the most cost efficient solution. The comparison to the new buildings shows that the GHG emissions increase significantly and the heat price is slightly lower mainly due to the consumption related costs. However it should be noted critically, that this result does not indicate that the supply of the building stock is more cost efficient. The result only indicate that the supply of a system with a higher energy demand (representing more customers) would be more cost efficient, for that reason this result is only comparable to a very limited degree. The results of the space demand and flexibility are comparable to the corresponding variants of the new building clusters from proportional point of view. However due to the increased heat demand, the space demand for installing components (solar collectors, BHEs) is higher by up to two times.

The technological comparison demonstrates that the application of exergy as a sole evaluation parameter highlights the importance and necessity of demand-adapted supply based on renewable energies, but in combination with selected evaluation parameters the meaningfulness is increased. Based on the findings it can be concluded that the exergy evaluation of community supplies should always be combined with the evaluation of energy efficiency, GHG emissions, costs (economic analysis), space requirement and future technological development (flexibility).

7.6 Comparison of selected scenarios

As part of the previous chapters a comprehensive technology comparison has been carried out were all parameters are evaluated individually. In this section it is aimed to compare selected energy systems directly to each other to identify possible advantages and disadvantages of the selected supply concept. Furthermore the results are ranked to identify the most suitable option for the supply of the new building cluster taking into account the constrained conditions. For this purpose the hard- and soft assessment parameters defined in chapter 5 are used and applied simultaneously.

For the overall comparison, only selected variants of the new building cluster are used. The selection is based on the most promising variants with regard for practical implementation (Schmidt et al. 2017; Sipilä, Rämä 2016; Eicker 2012). As a result, all monovalent configurations (NG boilers, heat pumps (HP) and CHP) and the combination of HP and CHP are selected. Furthermore the scenarios combining heat pumps respectively CHP units with solar thermal collector (solar fraction of 40 %) are investigated.

For the comparative analysis, the results are first brought to a uniform scale by converting the absolute values into relative values from zero to one. Variants with a value of zero indicate a low performance and variants with a value of one indicate a high performance. The conversion is based on the following formula:

$$f_{Performance} = \frac{x_{j,n} - x_{min,j}}{x_{max,j}} \qquad (7\text{-}1)$$

For a comparative discussion of different results as in the present case, the method of Multi-Criteria Analysis (MCA) is also possible. This method often uses weighting factors to assign different priorities to the studied categories (Sager-Klauss 2016). However, this is not aimed as part of this study. The aim is to determine and compare the advantages and disadvantages of the different variants.

The following questions are to be answered in the direct comparison of the different supply scenarios:

- **Overall energy efficiency (η_{Sys}):** Which variants have the best energetic performance compared to the other variants?
- **Overall exergy efficiency (Ψ_{Sys}):** Which variants have the best exergetic performance compared to the other variants?
- **Cost-effectiveness of the heat price (€/kWh):** What is the most economical supply option in comparison to the other variants?
- **GHG balance of the CDE (kgCO2eq/a):** What potential savings can be expected in comparison to the other variants?

Hard Evaluation Factors (HEF)

- **Space demand (based on the determined weighted area units WAU):** What potential savings can be expected in comparison to the other variants?
- **Flexibility in future energy systems:** What is the potential for the flexibility of the considered variant compared to other variants?

Soft Evaluation Factors (SEF)

The spider graphs used in Figure 7-29 show a comparison of the centralized variants with the decentralised NG boiler (D1) which could be seen as a standard solution for the heat supply in German buildings (see also discussion in chapter 6.2 and (Loga et al. 2015)).

As already shown in the previous chapters, the NG boiler (C1) in all cases shows the best performance with regard to energy efficiency. This is due to the high efficiency of condensing boilers, but also to the very low storage and distribution losses. The good economic performance results mainly from the low investment costs for the plant, as well as no need for a distribution network (gas and heat). The space demand is also very low since not thermal grid or storages are required. The decentralized variants, in particular the combination of solar thermal collectors and CHP plan, show a better performance regarding the exergy efficiency as well as the savings potential with regard to GHG emissions and flexibility.

The comparison of the centralised variants demonstrates that the scenario CHP has the best energetic performance compared to the other centralised variants. Also the combination of a ground source heat pump (GSHP) and CHP plant as well as the centralised GSHP shows advantages with regard to energy efficiency. The combination of solar thermal energy with CHP and GSHP is not very beneficial, since the high losses in seasonal storage have a negative impact on energy efficiency. In case of the decentralised variants the GSHP shows advantages over the centralised variants expecting the centralised CHP supply. As already been said, the decentralised variant D1 (reference) shows the best energetic performance.

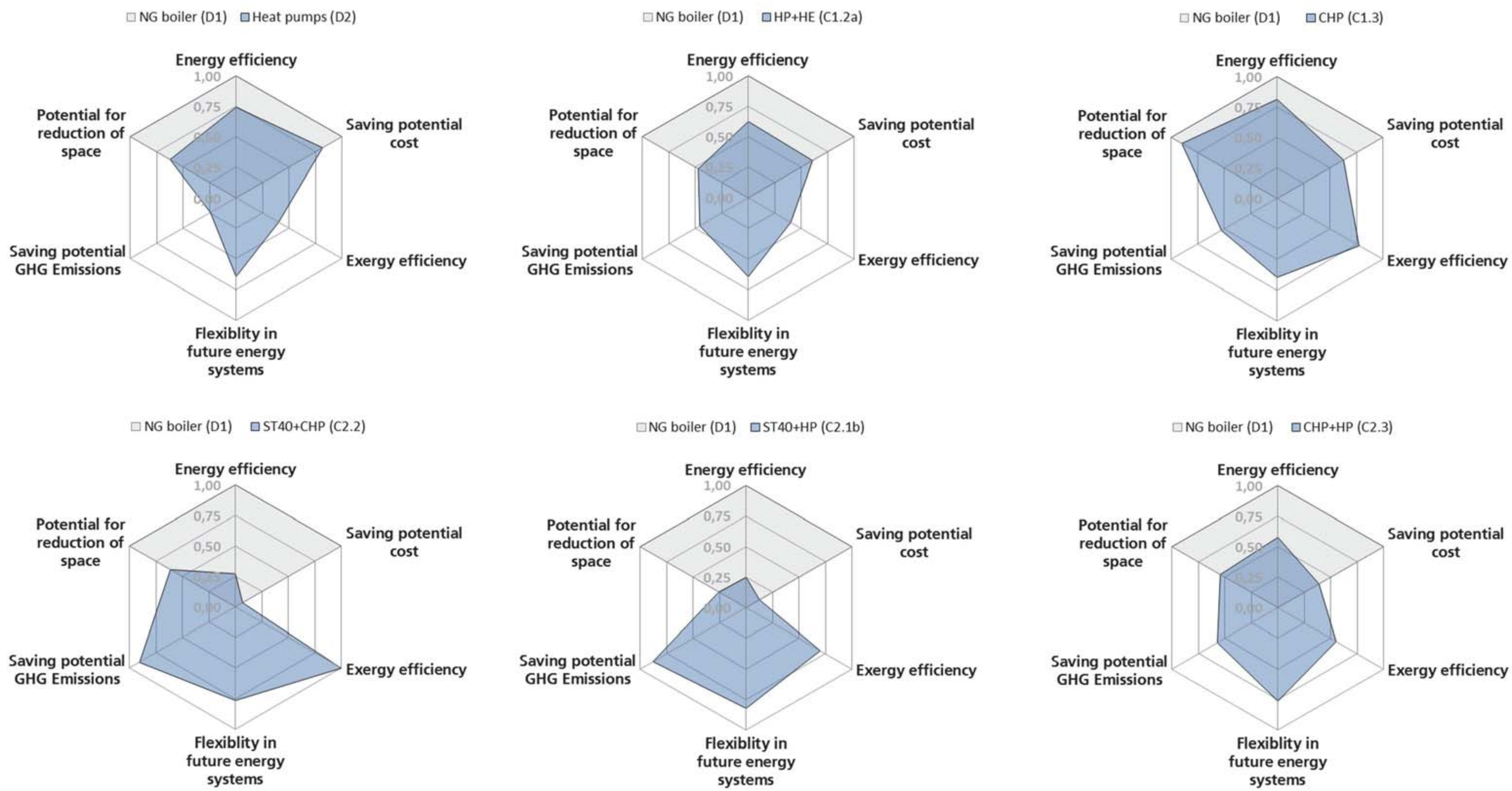


Figure 7-29: Comparison of the decentralised heat pumps (D2) and selected centralized variants (C1-C2) of the new building cluster with the reference variant “NG boiler (D1)”.

In contrast, the centralised variants using solar thermal collectors have the best exergy efficiencies due to the significant reduction of consumption of high quality fuels. The combination of the CHP plant and the solar thermal collectors shows the best performance with regard to exergy efficiency. The result is due to the use of solar thermal collectors (low quality sources) and the evaluation of CHP by the Carnot method. Also the monovalent CHP (C1.3) shows advantages with regard to this evaluation parameter. In direct comparison, the performance of heat pumps is slightly lower. Due to the high SPF, the heat pumps use a comparatively high proportion of low-quality environmental heat (geothermal energy), however, the use of (high-quality) electricity is also necessary for the supply of the compressors. The decentralised heat pumps (D2) show a lower degree of exergy efficiency in comparison to the centralised heat pumps, because of additional power demand. The decentralised scenario using NG boilers (D1) has no advantages with regard to exergy efficiency.

The most cost-effective variant in case of the centralized scenarios is the centralised CHP unit, which is in particular due to the proceeds of the electricity. Furthermore, no geothermal field or solar thermal collectors with seasonal storage are required. The centralised variants using solar thermal collectors or borehole heat exchangers have the lowest potential for savings, mainly due to the high investment costs of the storage devices but also for the collector field (solar thermal arrays and geothermal probe field). The most cost efficient solution is expected in case of decentralised NG boilers.

The highest potential for GHG savings can be expected in case of the variant, where a CHP unit is combined with solar thermal collectors. The result can be traced back to the generation of electricity and the usage solar energy, which in turn has a positive impact on the carbon footprint. Also the combination of GSHP and solar thermal collectors show high potentials for the reduction of GHG emissions due to the high performance factors. In contrast the decentralised variants show only low or no saving potential.

The lowest space requirement, as an indicator for reduction of space, is shown in case of the NG boiler, since only a gas grid is required in this scenario. With regard to the centralised supply variants the CHP shows high potential for effective use of space since no collectors (probe field or solar thermal collector) or a seasonal storage are required. In all scenarios using solar thermal or geothermal energy, the demand for space for the collectors has a negative effect on the potential for effective use of space. The lowest potential for saving of space is given in scenario ST40+HP (C2.1b), because of the space demand for the seasonal storage, the geothermal probe field and the solar collectors.

When considering the flexibility potential for future energy systems, it can be noticed that all central supply concepts and the decentralised GSHP have similar good performance. This is due to the fact that all central variants have a high degree of innovation (e.g. using RES or a low temperature local heating grid). However, a precise study highlights that a combination of solar thermal collectors which utilize a large seasonal storage and heat pumps offer the highest potentials. In contrast the NG boiler has very small advantages only due to the installed heating rods.

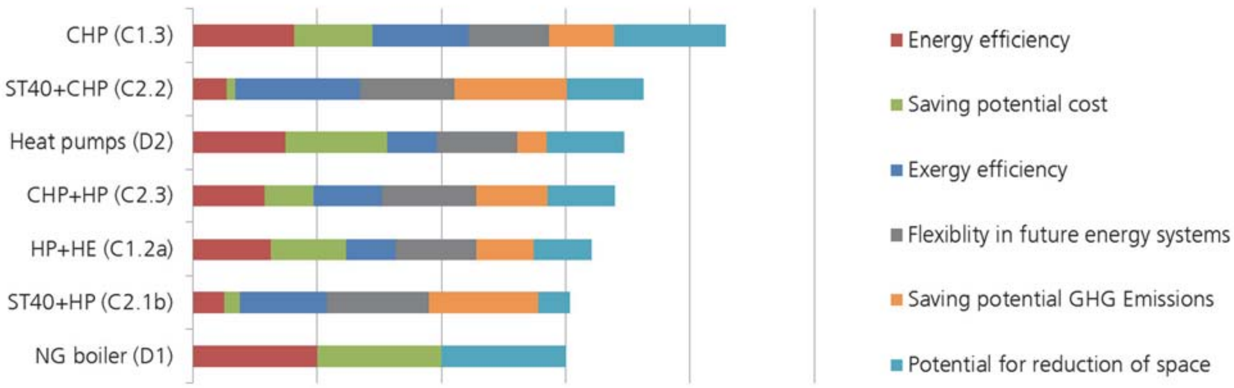


Figure 7-30: Comparison of the selected supply variants.

If all variants are compared by a ranking (see Figure 7-30) the overall best performance is given by the centralised CHP. In particular the proceeds and the credit of the electricity generation (GHG emissions and cost) but also the assessment of the CHP by using the Carnot method (exergy) have a positive impact on the overall evaluation. The advantage of these evaluation criteria respectively methods also have a positive effect on the variants where a central CHP is combined with solar thermal collectors. Nevertheless, the seasonal storage as well as the earth probe fields and the solar collector arrays have less positive effects on the overall assessment. These results can in particular be attributed to the costs and thermal losses but also space demand. The least advantageous variant is the decentralised gas boiler, since this scenario is the most unfavorable with regard to the demand-adapted supply and GHG emissions but also with regard to its flexibility in future energy system.

When considering the results it must be critically taken into account that in the course of the generic case studies a very small supply area with only a few customers is investigated. In the case of larger supply areas, the effects of single evaluation criteria (e.g. costs) could be less pronounced. In addition, these scenarios should compare to further supply technologies in order to identify the optimal supply concept for a particular location.

However it can be concluded that the results highlight possible advantages but also technological challenges and barriers of the used supply technologies in low temperature district heating schemes. Accordingly possible trends can be derived for the supply of new housing areas where a high degree of innovation and use of RES is desired.

8 Conclusions and Outlook

8.1 Overall summary and conclusion

Low temperature district heating (LTDH) offers new possibilities for efficient energy supply with a reduced consumption of fossil fuels (Lund et al. 2014). It facilitates the integration of renewable energy sources or excess heat, which is often available at fairly low temperature levels. For the analysis of LTDH the exergy analysis is a appropriate method since it indicates how well the thermodynamic potential of energy resources is being used (Schmidt et al. 2016b). However exergy evaluation does not inherently include other objectives such as maximizing the use of renewables or minimizing emissions and costs, which are often of particular relevance in real implementation projects (Kallert et al. 2017; Jansen, Meggers 2016). Accordingly a consistent, exergy-based assessment method for small scale low temperature supply systems was developed in which energy as well as economic and sustainability aspects are brought together. In the course of technology comparison, the approach was applied to generic case studies in order to proof the applicability of the assessment method in a first step and to derive the advantages and disadvantages of different supply technologies in a second step.

For the development of the exergy-based evaluation approach and the implementation of the technology comparison, three subtasks were defined. These represent as well the mile stones of the thesis.

Subtask 1: Modelling and simulation of small scale energy systems

As part of this subtask a small energy system (building group) consisting of ten residential buildings was modelled (TRNSYS17 2014). In order to reflect new buildings as well as existing buildings, a simplified building typology (buildings age classes) for German residential buildings in accordance with (Loga et al. 2015) and common standards as well as regulations e.g. (DIN V 18599-2: 2011-08) was elaborated. As part of the modelling process of the buildings a VBA-tool has been developed, which allows the generation of randomized user-profiles for space heating and PWH supply. To supply the buildings with heat, a local low temperature district heating grid (LTDH) with substations, storages and heat generation units was modelled. Since the target was set on a supply based on renewables for the building group, solar thermal collectors (ST), ground source heat pumps (GSHP) and gas-fired combined heat and power (CHP) were integrated as centralised energy suppliers in the model. Depending on the studied supply unit, a storage tank and seasonal storage were used to store the generated heat. To compare centralized and decentralised supply options, the model was also workable without a LTDH grid. To obtain an optimised supply of the building group, several control strategies for the energies suppliers were developed and implemented in the model. The model is characterized by high flexibility in the user interface, since "switches" were implemented to activate or deactivate the components of the model.

The central outcome of the first task is the model of a local heating network with a high level of detail for high-resolution simulations. Since the simulation model was not developed for a specific application (e.g. an implementation project), but for a technology comparison of several defined supply concepts it can easily be applied to other (generic) case studies due to its high adaptability. Furthermore the calculation methods collected and developed in this task provide a good basis for designing and dimensioning of small scale energy systems in general.

Subtask 2: Development of a consistent exergy-based assessment method

In the course of this subtask a consistent exergy-based evaluation method for a small scale district (building group) has been developed. The method is mainly based on the approaches of (Torío 2012; Torio, Schmidt 2011) and were further developed to allow the assessment of low temperature district heating supply systems. Accordingly for consistent assessment, the system boundaries for evaluation were re-defined and the mathematical description of different energy suppliers (e.g. heat pumps and CHP), storage devices (e.g. seasonal storage) and the district heating system (e.g. substations) were further developed and added to the method. Additionally an evaluation approach for fossil fuels and (fluctuating) renewable energy sources (primary energy input) were elaborated based on (Jentsch 2010).

For an efficient district heating supply, exergy indicates how well the working potential of an energy source is used. The exergy concept can be linked to economic and ecological parameters but does not necessarily cover other optimisation targets for instance maximizing the use of renewables or minimizing emissions or costs (Schmidt et al. 2016b). For that reason, additional technological evaluation parameters were identified and added to the exergy analysis developed in this thesis. Since the main focus was on technical comparison of several predefined systems and not on the optimisation of single components of the energy system, the evaluation parameters were regarded independently. For the evaluation of the energy supply, the following parameters were used: Energy and exergy efficiency, CO_2 emissions (environmental impacts), costs (economic analysis), space requirements and future technological development.

The main output of this second task is a consistent exergy-based assessment method for small scale energy systems, which can be used to increase the efficiency of small scale district heating supply schemes. In contrast to other research projects (Bargel 2010; Jentsch 2010; Torío 2012), the developed evaluation method is characterized by the fact that the exergy is not used as the sole evaluation parameter, but is seen in context with other important parameters. Furthermore, the evaluation is extended in a way that not only individual buildings, but also the entire supply infrastructure at district level can be assessed.

Subtask 3: Technological comparison of different supply scenarios and application of the method

As part of this subtask a comprehensive technological comparison was carried out. The technological comparison was used to demonstrate the usability of the exergy-based assessment method developed in subtask 2 and to prove the hypothesis that exergy is a central indicator for the optimisation of heat based processes on a district level. Furthermore advantages and disadvantages of the energy supply as well as challenges and barriers for practical implementation have been identified. Based on an extensive literature research, various decentralized and centralized supply options for new and existing buildings based on renewable and fossil fuels were identified and implemented in the model developed in subtask 1. In the course of the technology comparison the defined cases were analysed. The analyses included the comparison of different centralised and decentralised supply scenarios, based on fossil and renewable energy sources. The different supply units were regarded individually or in two- or three-unit combinations.

The results of the technology comparison demonstrate that in comparison to conventional energy analysis, exergy analysis is less sensitive to thermal energy losses in the overall energy system. Even if the overall thermal energy losses of the energy system (e.g. district heating grid or storage tank) are several times higher in comparison to standard solution (e.g. condensing boiler), exergy analysis leads to the conclusion that the use of low temperature sources is more favourable. In this way exergy assessment promotes the use of low valued energy sources instead of the use of high shares of high quality energy sources even if the energy conversion is highly efficient. The evaluation related to the GHG emissions shows similar conclusions as the exergetic evaluation. Nevertheless, no quantitative conclusion can be drawn solely based on energy or exergy analysis regarding maximization of renewables within the system or minimizing the emissions. This is in particular true for the supply to existing buildings. Additionally, in the case of real implementation projects, economic efficiency is an important factor in determining whether a system will be realised or not. In contrast to the assessment parameters discussed above it is shown that the use of centralised renewable energy supply in most cases leads to a higher number of plant facilities (collectors, storages and networks for distribution) and lower supply temperatures, which results in higher overall costs. This effect is also disadvantageous with regard to the space demand. In urban areas the building space is limited and expensive but also in rural areas the space available for plant components (e.g. solar collector arrays) can be limited since for instance agricultural use of the area is more preferred e.g. due to economic reasons. The share of fluctuating RES from PV and wind energy in the electricity mix is increasing. While they are becoming an increasingly important source of energy supply they also provide a significant challenge for the transmission capacities in the energy systems in general. The heating grid in combination with the selected energy suppliers offers great potentials for sector coupling and a flexible and supply driven operation. For that reason “flexibility options” in the electricity system as well as the possibilities of the heat market to stabilize the electricity market have to be taken into account in the evaluation of the systems. These issues will become more important with the upcoming transition of the electric energy system and might dominate future economic evaluations.

The investigations in the context of the technology comparison show that the method is adjustable and ready-to-use for the analysis of case studies where increased efficiency by demand adapted supply is targeted. The results of the technological comparison furthermore demonstrate that exergy assessment should always be combined with further evaluation parameters in order to identify technological advantages, challenges and barriers of supply technologies. However, exergy assessment as a sole evaluation parameter highlights the potential of innovative low temperature district heating supply based on a sound thermodynamic basis. Only in this way an important contribution can be made to increase the efficiency of energy supply and the transparency in the comparison of supply alternatives. In addition, low-temperature supply concepts will be promoted in this way, which will play a key role in the successful implementation of the energy transition. For that reason exergy should always be applied as a standard evaluation indicator when assessing district heating supply.

8.2 Outlook

From the findings of the present work, various approaches and issues for future research topics emerge.

- **Verification of the influence of the size of the examined supply area:** In the course of the technology comparison a very small supply area with only a few customers is investigated. This is particularly useful when the influence of individual buildings (e.g. user behavior) or individual suppliers (e.g. availability of solar heat) on the network is to be quantified. However, the size of the building groups mainly influences the economics of the supply concepts (e.g. heat pump electricity tariffs but also running times of the supply units or financing opportunities). In order to minimize this effect and to identify further bottlenecks, a larger group of buildings could be investigated. As part of future work it would e.g. be possible to assess the influence of the degree of connection on the performance of the network and to assess the influence of lowering the return temperature on the overall plant performance.

- **Investigation of further, innovative supply technologies (cascading):** In the course of further investigations, the potentials of cascading possibilities for the heat supply could be demonstrated (Gudmundsson et al. 2014). For example, it is conceivable to connect subnets with a low temperature level to the return line of district heating grid with a higher temperature level in order to achieve a more efficient use of the available energy and to increase the plant efficiency.
- **Investigation of further, innovative supply technologies (decentralised feed-in by using prosumers):** In a LTDH, the consumer can also be a producer at the same time and can supply heat from different, also regenerative energy sources. This principle is also known as "prosumer" (Nord et al. 2017). For the implementation of prosumers, the network must be flexible with respect to the feed-in and heat consumption. In particular industrial and commercial waste heat, decentralized renewable energy systems such as solar thermal energy and heat pumps combined with photovoltaics and CHP plants show high potential in this context. The integration of renewable energies increases the share of heat generation. Therefore, the concept can contribute to the energy transformation in a significant way and shows furthermore high potential for the coupling of the sectors "renewable electricity" and "heat".
- **The role of district heating in sector coupling "RES electricity - heat":** Low temperature district heating systems, in particular fed by heat pumps and cogeneration units, are a key technology in context of the sector coupling "RES electricity - heat". Against the background of increasing shares of fluctuating electricity from renewable energy sources (RES) of the "grid supportivity" respectively the "market supportivity" can be investigated. New control strategies and new flexibility options have to be developed for this purpose.
- **Transferability of results and transformation of district heating systems:** In the course of the technology comparison, new construction areas as well as existing residential areas (German building stock) were examined. The transformation of district heating systems in general is a challenge against the background of the energy transition (in particular heating sector) (Rämä, Sipilä 2017). Using the approaches developed here, key figures could be developed, which can contribute to the success of the energy transformation.

The number of possible future research topics highlights the relevance of the subject of the work. Hence a high potential for future research based on the results discussed in this thesis can be derived. In particular, the transformation of the German energy system and sector coupling (RES electricity and heat) as well as the rising importance of district heating in the context of the energy transition will more and more characterise future research activities. In addition to the technological issues, also questions of the operational models will become increasingly important.

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Nomenclature

Latin characters

A	Area	[m²]
a	Constant factors	[-]
B	Thermal conductivity of the pipe	[W/mK]
c	Specific heat capacity	[J/(kgK)]
d	Diameter	[m]
En	Exergy	[J]
Ex	Energy	[J]
$\dot{En}$	Energy rate, power	[W]
$\dot{Ex}$	Exergy rate, power	[W]
F	Quality factor	[-]
f	Factor	[-]
h	Height dimensionless heat loss factor	[m]
H	Dimensionless heat loss factor	[-]
k	Surface roughness	[-]
l	Length	[m]
L	Length (standard)	[m]
m	Mass	[kg]
$\dot{m}$	Massenflow rate	[kg/s]
P	Power/ Electric energy demand	[J] / [W]
p	Pressure / primary energy	[Pa] / [kWh]
Q	Heat	[J]
$\dot{Q}$	Heat flow rate	[W]
$\dot{q}$	Specific heat flow rate	[W/m²]
q	Spezifische Wärmeleistung	[W/m²]
r	Radius	[m]
R	Thermal heat Resistance	[K/W]
Re	Reynolds number	[-]
T	Absolute temperature	[K]
t	Time / temperature in degrees Celsius	[s] /[°C]
U	Heat transfer coefficient	[W/m²K]
V	Volume	[m³]
$\dot{V}$	Volume flow	[m³/s]
w	Velocity	[m/s]

Greek characters

α	Heat transfer coefficient	[W/(m²K)]
β	Quality factor	[-]
Δ	Difference	[-]
ζ	Pressure loss coefficient	[-]
ϑ	Temperature in degrees Celsius	[°C]
η	Energy efficiency	[-]
λ	Thermal conductivity, starting value iteration	[-]/[W/(m K)]
ρ	Density	[kg/m³]
σ	Fraction	[-]
υ	Kinematic viscosity	[Pa s]
τ	Time	[s]
Φ	Standard heating load	[W]
ψ	Exergy efficiency	[-]

Indices

0	Reference environment/ Reference point 0
1	Reference point 1
2	Reference point 2
A	Area
a	Air
a	Year/ Obervation period
amb	Ambient / Reference environment
Alloc	Allocation
B	floor coverings
Bui	Building
ch	chemical
CHP	Combined heat and power
coll	Collector / Collector fluid
cons	Consumed
const	Constant
CW	Cold water
D	External pipe diameter
dem	Demand
dest	Destructed
DH	District heating
DHW	Domestic hot water
dis	Discharge process
E	Building Equipment
em	Emission
env	Envelope
el	Electric, electricity
fuel	Fuel
h	Heating
HL	Heating load
HX/ hx	Heat exchanger
HW	Hot water
i	Reference point, running variable
in	Inlet
J	Running variable
Irr	Irreversibel
k	unning variable
LHV	Lower heating values
lm	Logarithmic temperature difference
loss	Losses
m	Mass/ mass bound/ running variabl
max	Maximum
mix	Mixing
n	Number
op	Operative
overall	Overall
out	Outlet
p	Constant pressure
pipe	Pipe
prim	Primary
pump	Pumps
PWC	Potable water cold
PWH	Potable water hot
Q	Heat source

R	Return
Rad	Radiator
ret	Return
RL	Return Line
S	Supply
SH	Space heating
single	single
SL	Supply line
soil	Soil
sol	Solar
ST	Solar thermal collectors
stand	Standard, calculated according to standard
store	Stored
sup	Supply
sys	System
TB	Thermal bridge
th/therm	Thermal
Trans	Transmission
tot	Total
use	Useful energy
V	Ventilation
w	Water

Acronyms

4GDH	4^{th} Generation District Heating
BHE	Borehole heat exchanger
BS	Buffer storage
CDE	CO_2 equivalents
CF	Carnot factor
CHP	Combined heat and power
COP	Coefficient of Performance
CW	Cold water
DHW	Domestic hot water
FLT	First law of thermodynamics
GDH	Geothermal district heating
GHG	Greenhouse gas emission
GSDH	Solar district heating
GSHP	Ground source heat pump
HC	Heating centre
HE	Heating element
HEX	Heat exchangers
HEF	Hard evaluation factor
HP	Heat pump
HW	Hot water
KfW	Kreditanstalt für Wiederaufbau
LHV	Lower heating value
LTDH	Low temperature district heating
NG	Natural gas
NN	Network Nodes
P2H	Power to heat
PVT	Photovoltaic thermal hybrid solar collector
PWC	Potable water cold
PWH	Potable water hot
Rad	Radiation

RES	Renewable energy sources
SDH	Solar district heating
SeP	Service pipe
SEF	Seasonal performance factor
SF	Simultaneity factor
SFH	Single-family house
SH	Space heating
SLT	Second law of thermodynamics
SDH	Solar district heating
SPF	Seasonal performance factor
SS	Seasonal storage
SuP	Supply pipe
VAT	Value-added tax
VBA	Visual Basic for Applications
TRNSYS	Transient System Simulation Tool
WAU	Weighted area units

Appendix

A. Assumptions for the modelling and further assessment result

A1. Primary energy factors

In the course of the evaluation in chapter 7.1, the primary energy factors listed in Table A-1 were used in accordance to currently valid German standardization (DIN V 18599-1:2016-10; EnEV 2015). Based on the definition of the system boundaries (see chapter 3.1), it is assumed that the non-renewable fossil fuels and electricity are supplied to the energy system. In case of the use of renewable or environmental energy, it is assument that the energy is harnessed inside the system boundaries. The evaluation is carried out in accordance with (Bargel 2010; Hertle et al. 2014; Jentsch 2010; Schmidt et al. 2009).

Table A-1: Primary energy factor used for evaluation in accordance to (DIN V 18599-1:2016-10).

Fuels (reference value for final energy: calorific value)		Primary energy factors f_p	
		Total	Non renewables
	Final energy supplied to the system boundaries		
Fossil fuels and electricity	Heating oil EL	1.1	1.1
	Natural gas H	1.1	1.1
	General electricity mix	2.8	1.8
	Harnessed final energy within the system boundaries		
Environmental energy	Heat (geothermal energy, solar thermal energy and ambient heat)	1	0

A2. Radiation data and temperature of the soil

The following temperatures (see Figure A-1) of the soil were determined using TRNSYS (TRNSYS17 2014).

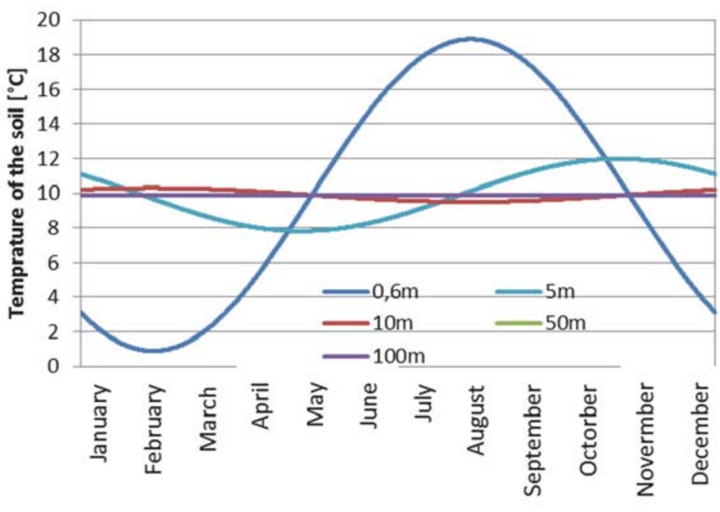

Figure A-1: Temperature of the soil determined with (TRNSYS17 2014).

When evaluating the district heating pipes, it is assumed that the pipes are laid at a depth of 0.6 m (see chapter 4.6.1). When evaluating the geothermal probes, it is assumed that the geothermal probes are at a depth of up to 100 m (see chapter 4.8.2).

The following radiation data and outside air temperatures were used in the simulations and the evaluation. The data were generated with (Meteotest 2015) for the city of Kassel and read-in by the TRNSYS model (see chapter4). The outside air temperature is particularly important for the exergetic assessment (see chapter 3) since it is used as a reference environment. Furthermore, it is used for the determination of the heating demand (see chapter 4). The radiation data are particularly important for the determination of the solar yield of solar thermal collectors (see chapter 4.8.1).

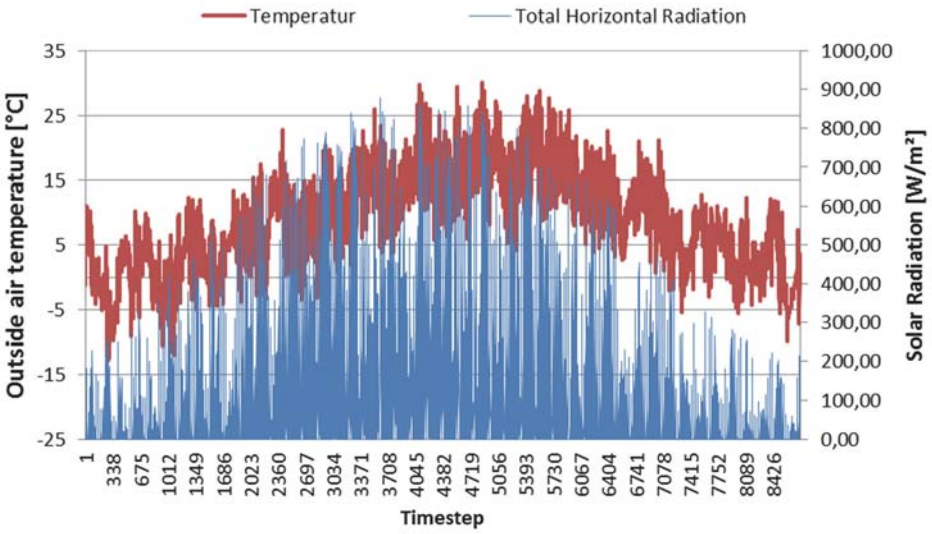

Figure A-2: Outside air and solar radiation determined with (Meteotest 2015) and (TRNSYS17 2014).

A3. Comparison of TUS of Great Britain and Germany

A time usage survey (TUS) from the UK is used as the database for the presence profiles used in the user profile generator introduced in chapter 4.3. Statistical data were used for the devices. The model is validated and complies largely with the UK standard load profiles (SLP)[22] for households. The latter (dashed line), in turn, is comparable to the German SLP for households, as shown in Figure A-3 (the labeling of the Y-axis has been omitted, since these are the same factors in both cases).

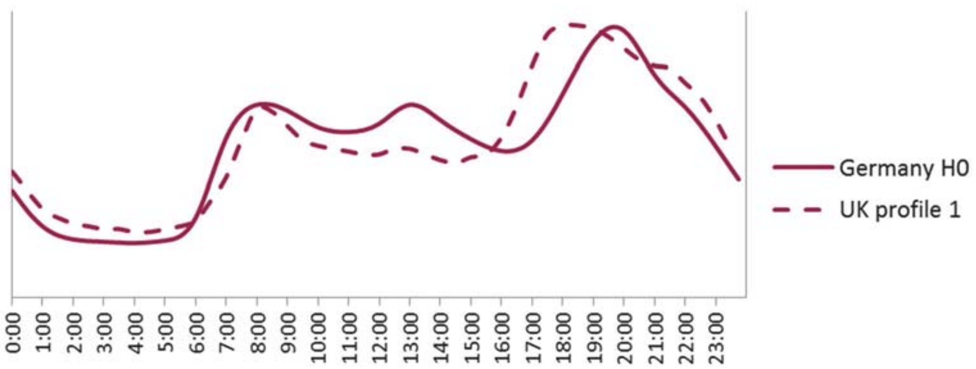

Figure A-3: Comparison of standard load profiles for households in the UK and Germany.

[22] Standard load profiles are used by energy supply companies for load prognoses in the electricity and gas networks. They represent different customer groups, e.g. households, business or agriculture.

The profiles are representing workdays at the wintertime. The comparison of other days showed less correlated courses. The TUS in Great Britain and Germany are also otherwise comparable. However, people in Germany leave the household on average 40 minutes earlier than in the UK and come back 80 minutes earlier (Bauer et al. 2007). However, these deviations are not reflected in the current profile, as can be seen in Figure A-3.

A4. Evaluation of the research questions

In chapter 1.3, several research questions were raised that were of particular importance for the implementation of this work. In the following, all research questions are answered:

How can the exergetic assessment method contribute to a more efficient and CO_2-neutral community supply? What is the advantage of the exergetic analysis compared to conventional energetic analysis?

Exergy assessment entails matching the quality levels of energy supply and demand. Since only a low energy quality is required for the space heating and potable water hot preparation in residential buildings, a low temperature supply based on RES (e.g. solar district heating) leads to a demand-adapted supply. In this way, the utilization of high-value energy resources, such as combustible fuels (e.g. NG boiler), are minimized. Since in turn combustion processes are primarily responsible for CO_2 emissions, the emission are reduced. This insight cannot be obtained with energy analysis. As result it can be concluded that in comparison to plain energy analysis, exergy based system optimization facilitates the integration of renewable heat sources that are most often available at fairly low temperatures.

Which parameters have to be combined with the exergy analysis to achieve a consistent overall picture for efficient, cost efficient and GHG emission free low temperature supply?

The exergy concept can be linked with economic and ecological parameters but does not inherently include other objectives such as maximizing the use of renewables or minimizing emissions or cost. For that reason additional technological evaluation parameters are identified which are added to the exergy analysis developed in this thesis. These parameters comprise energy efficiency, greenhouse gas (GHG) emissions, full cost analysis, but also space requirements and flexibility of energy supply in future energy systems.

As part of this thesis the evaluation parameters are regarded independently since the focus is on technical comparison of several predefined systems and not on optimisation of single components of the energy system. In addition, in the course of this thesis the advantage of the exergetic assessment for district heat supply is to be demonstrated. The potential of the exergetic analysis can be comprehensively examined only independent from other parameters.

What existing respectively innovative supply technologies have to be implemented or combined for future optimised energy systems on the community scale?

A literature study shows that solar thermal collectors and ground source heat pumps have the highest potential with regard to efficient use of freely available environmental energy at a low temperature level. In Germany, solar thermal energy is unrestrictedly available. Combined with other supply units, the use of fossil fuels or electricity can be significantly reduced. Brine-water heat pumps, such as the geothermal heat pump, have a high potential to utilize geothermal heat or other waste heat sources of any kind. They are comparatively safe in operation. Compared to air-to-water heat pumps, a better COP is achieved due to the mostly constant temperature level of the source.

However, the COP decreases significantly with increasing temperature demand, which is possibly an obstacle to the application of the technology in drinking water preparation. CHP units operate at a comparatively higher temperature level and do not necessarily use regenerative energy sources (for example, biomass) but are always available to cover basic loads. The greatest advantage is the simultaneous generation of electricity and heat. In this way the CHP unit becomes to a cost-efficient and flexible energy supply unit. If all these advantages are taken into account, solar thermal collectors, heat pumps and CHP units have the greatest potential for an energy-efficient supply. Furthermore, these units can be combined very well.

Is it possible to supply the German building stock based on renewable energy sources? What are the minimum required temperature levels of supply for new and existing buildings?

As part of the simulation studies, it turned out that it is possible to supply the German building stock with LTDH solely based on renewables. It is also demonstrated that the combination of different energy suppliers is possible. However, the solar cover rates (solar fraction) should be slightly lower compared to the new building supply. With regard to suitable supply temperatures, it turned out that a supply temperature of 75 °C for the existing buildings are optimal. These temperature levels represent the lowest possible temperature level to ensure secure of supply and user-comfort (both space heating and PWH). Furthermore the values are consistent with values that can be found in the literature (e.g. (Brand 2014))

Which advantages and disadvantages of the technologies and technology combinations are derived from the selected assessment parameters?

As part this thesis a number of generic case studies are investigated, where different energy suppliers are regarded individually or in combination.

The evaluation shows that the decentralised NG boiler is the best solution in case of energy efficiency due to the overall lowest thermal losses. The decentralized NG boiler is also the best supply solution with regard to terms of investment cost and heat price but also space requirements. The highest exergy efficiency and the lowest GHG emissions are achieved by the central scenarios that use a high proportion of solar energy or where a CHP unit is implemented. The highest potential in case of flexibility is achieved by the variants using big seasonal storage tanks or a district heat grid in combination with heat pumps or heating rods.

Due to the overall thermal losses in the system the combination of different energy suppliers does not lead to increasing energy efficiency. In contrast the suitable combination of different supply units leads to an improvement from an exergy point of view due to a significant reduction of high valued energy. A similar picture emerges with regard to evaluation of GHG emissions. The evaluation of economy and the space requirement shows, that the combination of energy suppliers has no advantage since specific heat price and the space demand rise in all cases. In contrast the combination of energy suppliers shows advantages regarding flexibility in future energy systems.

B. Overview of the simulation results

B1. Final energy and exergy demand of the buildlings

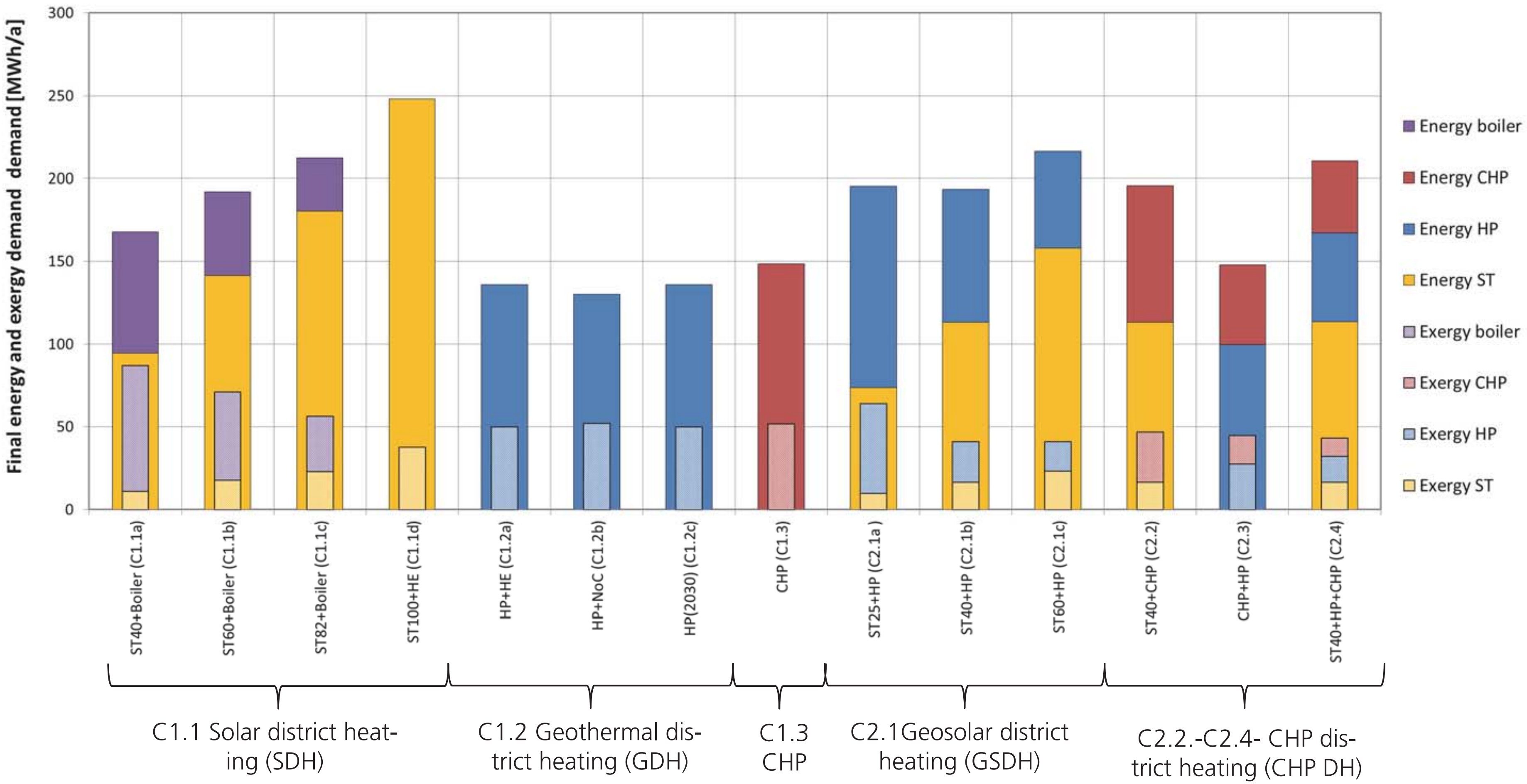

Figure B-1: Overview of the final energy and exergy demand of the new buildings cluster.

Figures B-1 and B-2 show the final energy and the exergy demand for the cluster of new and existing buildings. From the images, the fractions of the final energy demand of the respectively selected centralised supply units can be taken. The evaluation of the decentralized supply variants were not taken into account in the evaluation, since in each case only one supply unit is examined. The comparison of the results shows similar trends as the evaluation results in chapter 7.1. For example, it can be seen that the use of e.g. fossil-based energy supply units (peak load boiler) is reduced with a rising share of solar energy. This has also an impact on the energy and exergy demand. A rising solar share leads to an increase in energy demand while the exergy demand is reduced. Next to this, also the advantages of the combination of different energy supply from an exergy point of view can be derived. The comparison of Figure B-1 and B-2 show, that the demand of the existing builing cluster is higher. However, similar results can be derived for both building clusters.

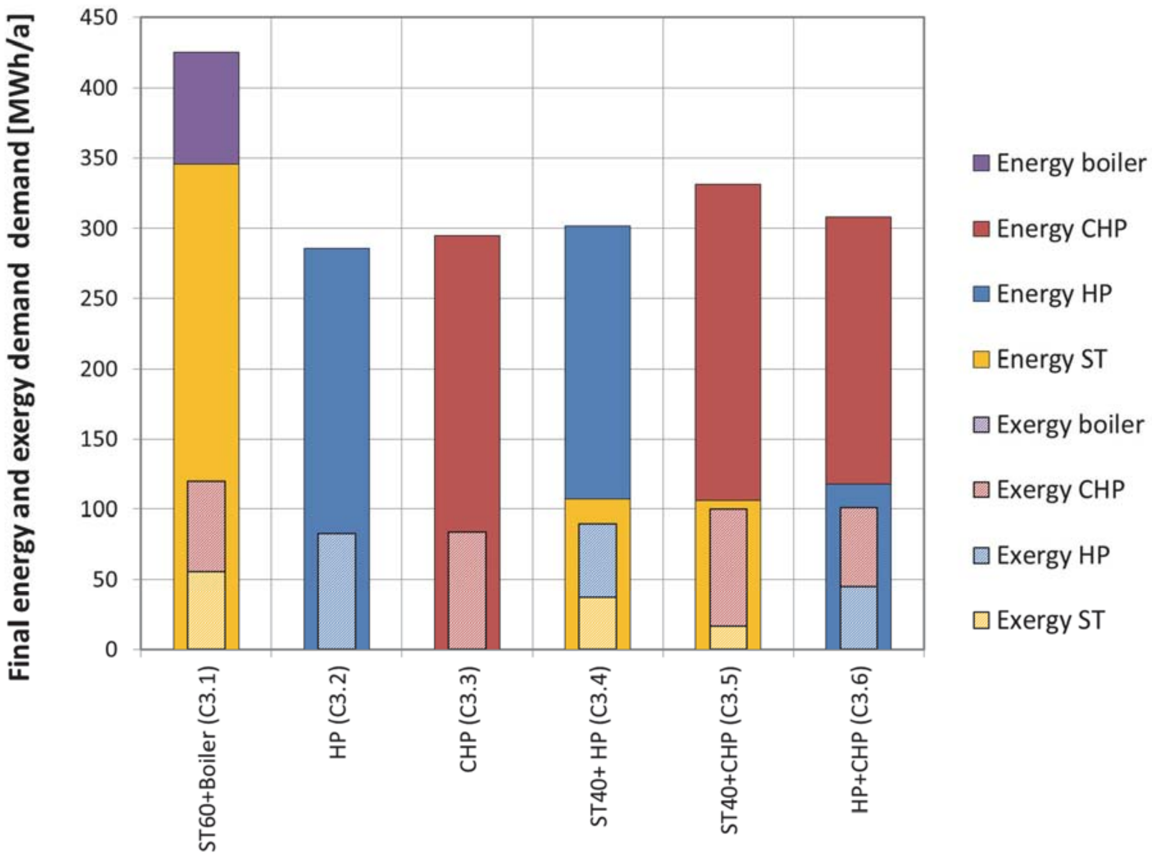

Figure B-2: Overview of the final energy and exergy demand of the existing buildings cluster.

B2. Simulation results of the energy suppilers

Table B-1: Overview simulation results of the variants C1 for the new buildings.

	Unit	C1.1 Solar thermal district heating (SDH)				C1.2 Geothermal district heating (GDH)			CHP (C1.3)
		ST40+Boiler (C1.1a)	ST60+Boiler (C1.1b)	ST82+Boiler (C1.1c)	ST100+HE (C1.1d)	HP+HE (C1.2a)	HP+NoC (C1.2b)	HP (2030) (C1.2c)	
Energy efficiency	%	67	60	55	48	75	73	84	83
Exergy efficiency	%	8	10	13	18	11	11	16	16
Solar fraction	%	41	59	79	100	-	-	-	-
Storage efficiency	%	85	79	74	69	89	95	89	89
Overall thermal losses	%	24	31	36	43	18	23	18	18
Thermal losses heating grid	%	4	4	5	8	4	4	4	4
Electricity demand (pumps)	kWh_{el}/a	2 000	1 948	1 875	5 098	2 592	1 865	2 592	1 591
Electricity demand (heating rod)	kWh_{el}/a	952	833	792	4 634	2824	7726	2824	524
Electricity demand (heat pump)	kWh_{el}/a	-	-	-	-	3 7567	3 4492	3 7567	-
Energy gain collector	kWh_{th}/a	94 601	141 198	180 354	245 269	-	-	-	-
Demand peak load boiler	kWh_{th}/a	73 245	51 016	32 059	-	-	-	-	-
Seasonal performance factor	-	-	-	-	-	4	4	4	-

Table B-2: Overview simulation results of the variants C2 for the new buildings.

	Unit	C2.1 Geosolar district heating (GSDH)			CHP district heating (CHP DH)		
		ST25+HP (C2.1a)	ST40+HP (C2.1b)	ST60+HP (C2.1c)	ST40+CHP (C2.2)	CHP+HP (C2.3)	ST40+HP+CHP (C2.4)
Energy efficiency	%	64	59	54	60	69	57
Exergy efficiency	%	13	14	15	19	13	16
Solar fraction	%	25	44	60	44	-	-
Storage efficiency	%	92	86	82	85	84	83
Overall thermal losses	%	21	24	31	24	24	24
Thermal losses heating grid	%	4	4	5	5	4	4
Electricity demand (pumps)	kWh_{el}/a	2 105	2 046	1 881	1 851	2 012	2 089
Electricity demand (heating rod)	kWh_{el}/a	606	645	668	624	624	609
Electricity demand (heat pump)	kWh_{el}/a	26 578	18 841	13 064	-	17 259	11 451
Energy gain collec-tor	kWh_{th}/a	73 630	113 525	158 311	113 525		113 525
Seasonal perfor-mance factor	-	4.3	4.4	4.6	-	5	4.2

Table B-3: Overview simulation results of the variants C3 for the existing buildings.

	Unit	ST60+Boiler (C 3.1)	HP (C 3.2)	CHP (C 3.3)	ST40+ HP (C3.4)	ST40+CHP (3.5)	HP+CHP (C3.6)
Energy efficiency	%	43	62	82	53	56	68
Exergy efficiency	%	8	6	13	11	14	11
Solar fraction	%	53	-	-	40	-	-
Storage efficiency	%	62	84	88	76	76	86
Overall thermal losses	%	41	26	28	34	34	
Thermal losses heating grid	%	10	7	8	6	8	7
Electricity demand (pumps)	kWh_{el}/a	3.647	2.166	1.731	2.343	1.905	1.835
Electricity demand (heat pump)	kWh_{el}/a	-	49.509	-	40.068	-	38.405
Energy gain collector	kWh_{th}/a	114.942	-	-	107.124	105.515	-
Seasonal performance factor	-	-	3.6	-	3.8	0	3.9

B3. Detailed overview of exergy consumption and energy losses in the system components

Figure B-3 and Figure B-4 show the evaluation of the energy and exergy flows of the supply variant of the scenarios of solar district heating suppy (SDH) and geothermal district heating (GDH) the occurring in the energy conversion chain in the building group. The process steps “Room” and “Envelope” comprise the entire building cluster.

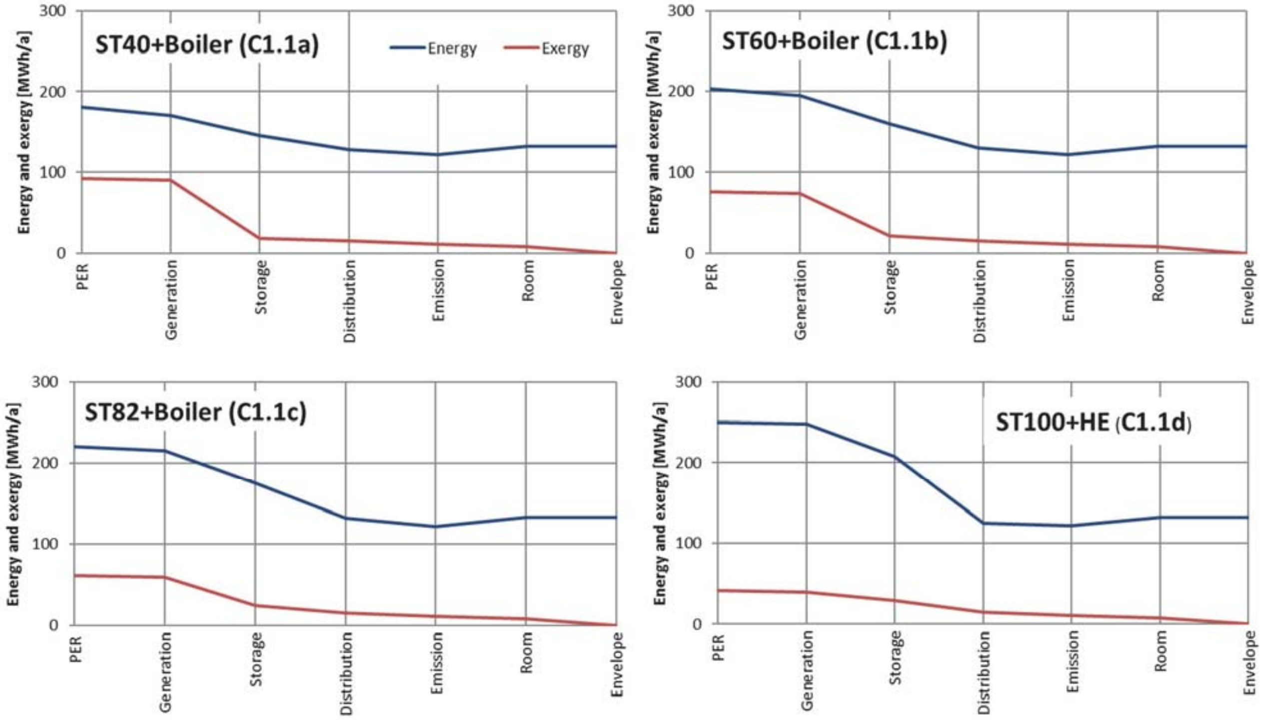

Figure B-3: Simulation results of the SDH district heating supply (T_{supply} =45°C).

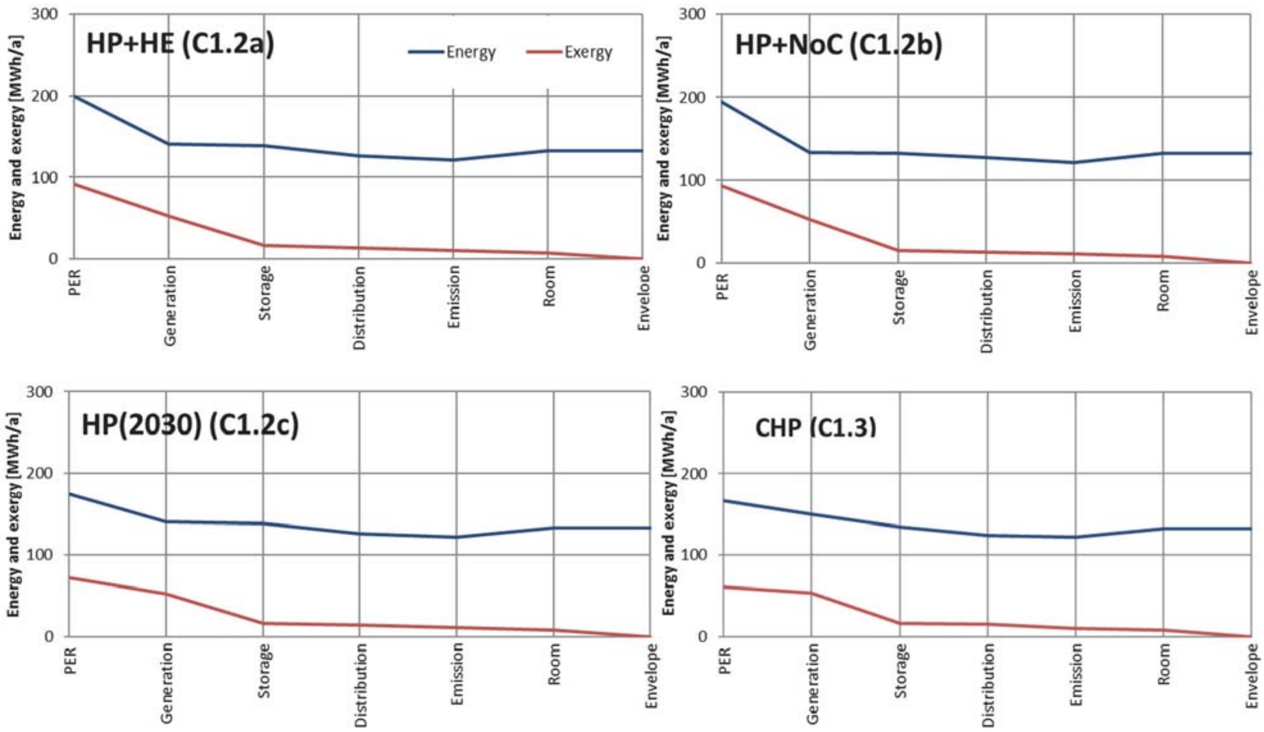

Figure B-4: Simulation results of the geothermal district heating (GDH) supply (T_{supply} =45°C).

Figure B-5 show the evaluation of the energy and exergy flows of the variants C2 (multi-generation for new buildings) occurring in the energy conversion chain. The process steps "Room" and "Envelope" comprise the entire building cluster.

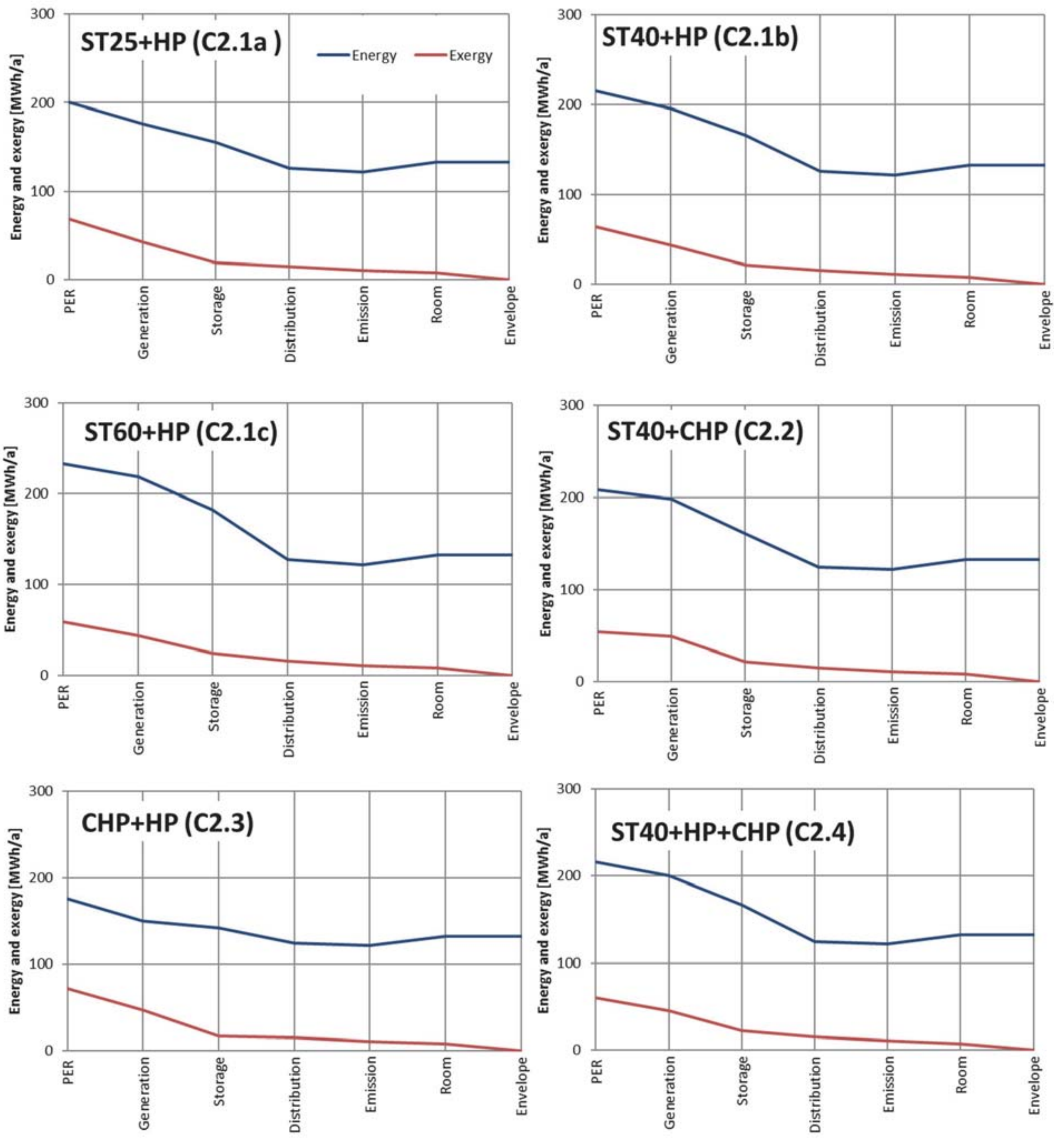

Figure B-5: Simulation results of the geothermal district heating (GDH) supply (T_{supply} = 45°C).

The overall analysis shows that the exergy is more sensitive to the energy supply unit respectively source used. The higher the thermodynamic working potential, the greater the destruction of the working potential or the losses (see "generation to storage"). Moreover, it turns out that the exergy can completely be consumed. This is due to the choice of balance limits respectively the reference environment. The energy in turn is more sensitive to the thermal losses or the thermal gains (e.g. solar gains through the windows). This becomes particularly clear in the process steps "storage to distribution" or "emission to room". These effects could be used to compare supply solutions and to optimize the building or district respective community supply.

Figure B-6 shows the evaluation of the energy and exergy flows of the variants C3 (supply of existing buildings) occurring in the energy conversion chain. When comparing the existing and new construction variants, it must be noted that the scaling of the representations has been changed.

The comparison of the supply options for the existing buildings shows similar effects as for the supply of new buildings. The comparison to the new cluster demonstrates that the solar gains are less pronounced and the thermal losses are more pronounced. The exergy consumption is slightly reduced, since more energy and a resulting higher supply temperature is required for space heating. It can therefore be concluded that the combined energetic and exergetic analysis is suitable for the assessment and optimization of new and existing buildings.

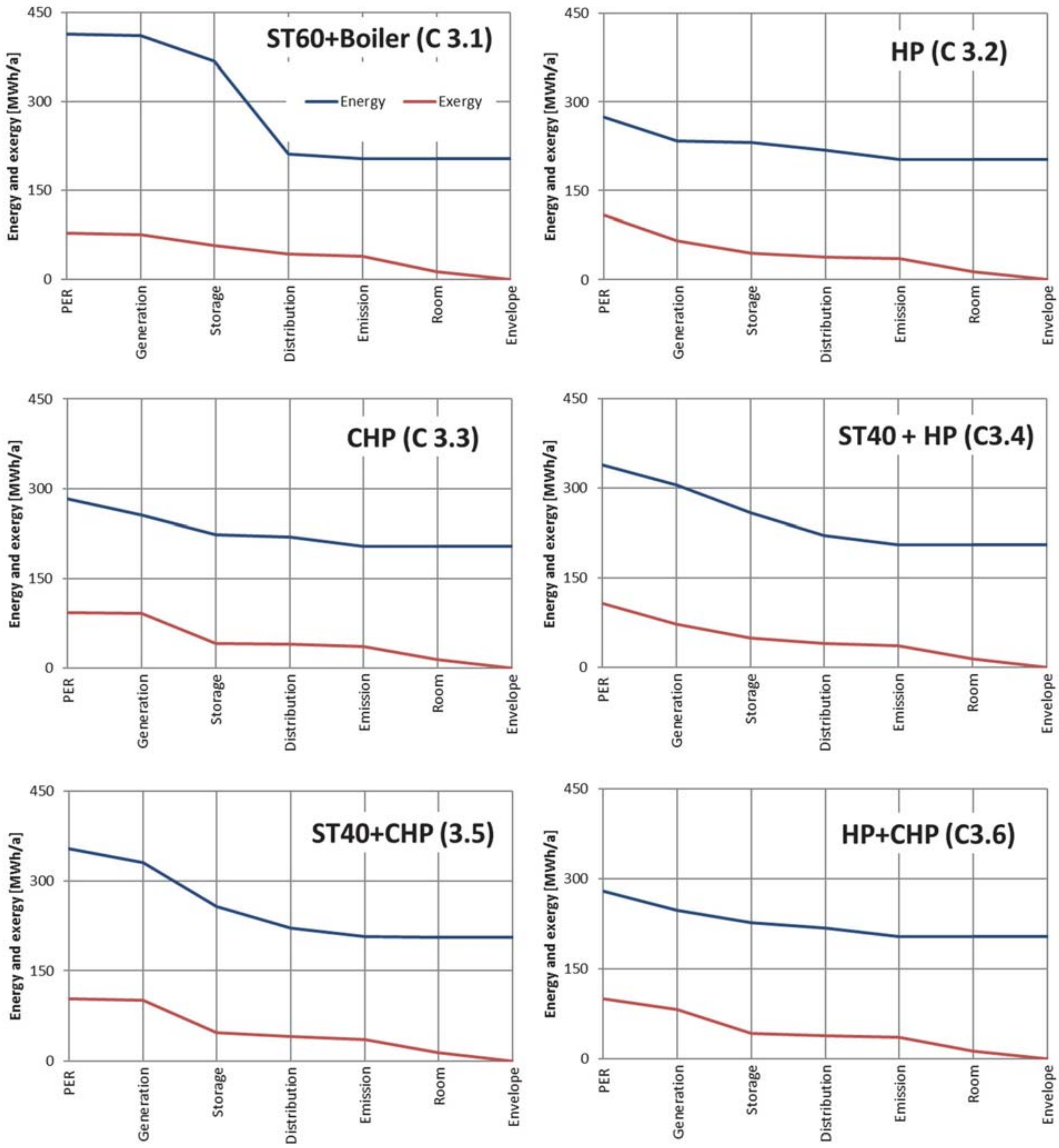

Figure B-6: Simulation results of the supply of existing buildings (T_{supply} = 75°C).

B4. Overview of the annual operation times of the differenet supplying units

Figure B-7 shows the running times of the supplying units using electricity (heat pumps and heating rods for DHW supply) or fossil fuels (peakload boiler and CHP) for scenario C1 (for further information see also chapter 6.3 and Table 6-2). As it can be seen, the eletricity demand for the heating rod and the demand of NG for the peak load boiler declines in the case where the solar fraction rises and the supply temperature drops.

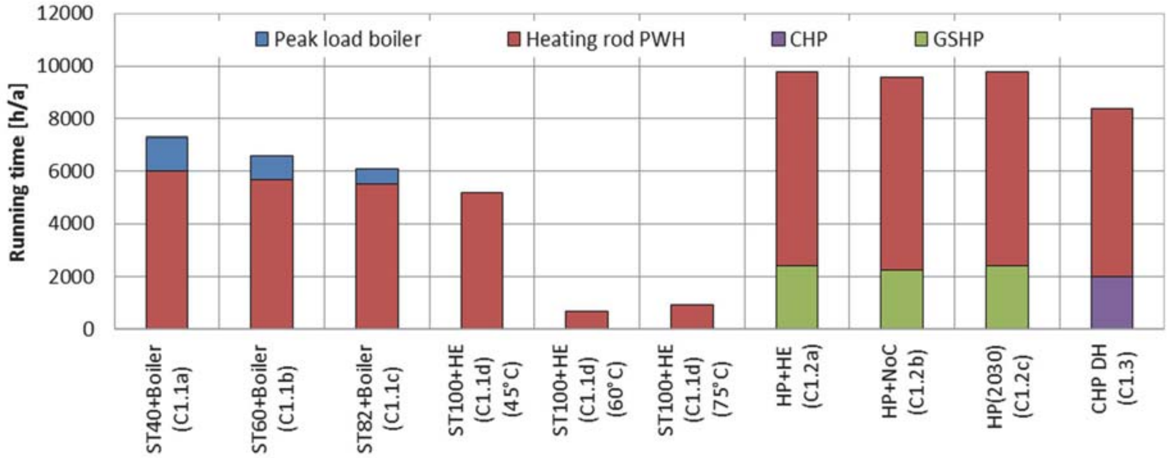

Figure B-7: Running times of the peakload boilers, heating rods, heat pumps and CHP units for scenario C1 (monovanlent supply for new buildings).

The running times of the different energy suppliers used in the centralised multi-generation scenarios (see also Table 6-3 in chapter 6.3.2) for the new buildings (C2) are shown in Figure B-8. It is demonstrated that an increase in the solar fraction and a temperature increase results in a reduction of the operating times of the heating rods and an increase in the operating times of the heat pumps. The highest running time is shown by a combination of three supply units.

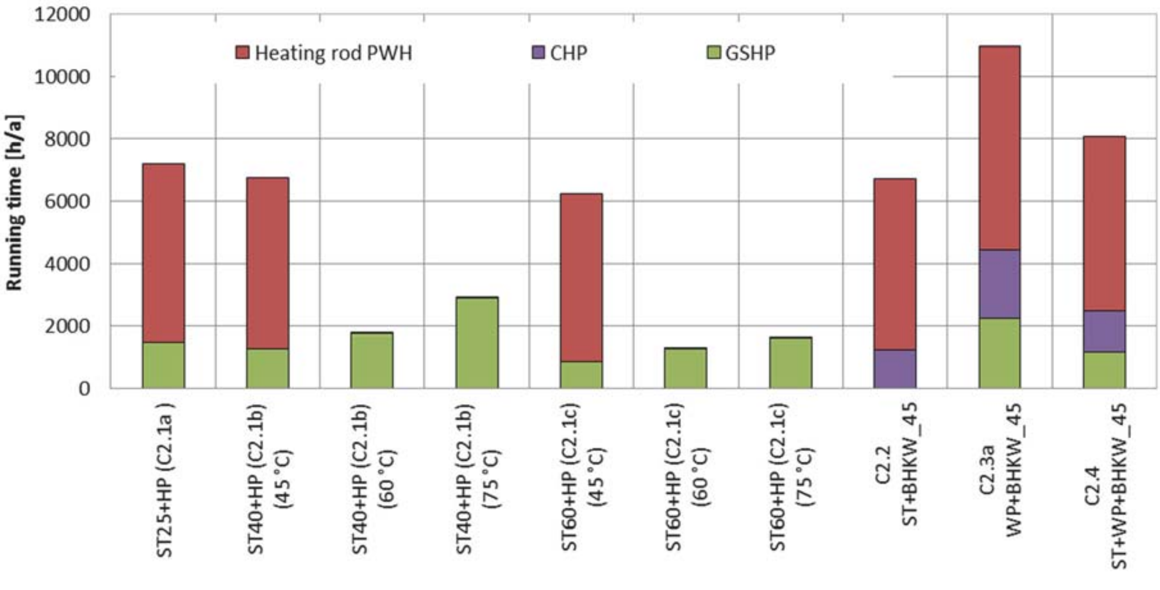

Figure B-8: Runnig times of the heating rods, heat pumps and CHP units for scenario C2 (multi-generation supply for new buildings).

In all cases of the supply scenarios of the new buildings, the heating of the drinking water has a decisive influence. This confirms the trend that, when the insulation standard is being improved, drinking water heating is gaining in importance.

The operating times of the energy suppliers of the scenarios of the existing buildings are shown in Figure B-9 (see also Table 6-4in chapter 6.3.3). It can be seen that a high utilization of the peak load boiler is required in case of high solar fraction. The highest overall operating time is required in case of the combination of heat pumps and CHP unit. The lowest running time is shown in case of the combination of the heat pump and the solar thermal collectors.

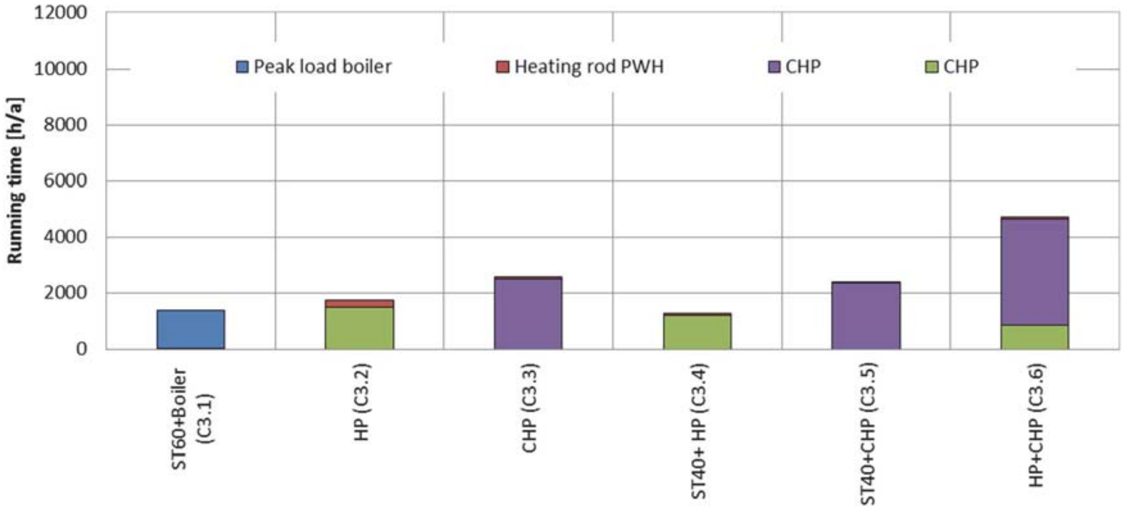

Figure B-9: Runnig times heating rods, heat pumps and CHP units for scenario C3 for the existing buildings.

Low temperature district heating (LTDH) offers possibilities for efficient heat supply based on renewable energies. For the analysis of LTDH, the exergetic assessment is a suitable method. Hence, an exergy-based assessment method was developed in which energy as well as economic and sustainability aspects are combined. As part of a technology comparison, the method is applied to case studies to verify the applicability of the assessment approach. The approach highlights innovative supply solutions by identifying the advantages and disadvantages of different supply strategies.

ISBN 978-3-8396-1435-8

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