MASTER’S THESIS

Definition and evaluation of parameters allowing for a sustainable district heating network operation

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Abstract

The study evaluates the performance of currently operated district heating grids of the company badenova WärmePlus. It defines determining factors in the economic as well as environmental performance which in turn, influence the technology's acceptance in society. Besides, the issue of decreasing heat demands which poses new challenges for the technology is tackled.

This is done in analyzing the internal and external influential framework and in describing the technological status quo. Hereafter a modeling of the operation performance of selected district heating grids is carried out. Calculations aim at an evaluation of whether the effective losses of the grids apply to the technological circumstances or whether measures need to be applied in order to derive better cost effectiveness. An NPV evaluation provides an insight into the potential profitability of such measures.

Another investment analysis is done on the basis of a fictional DH network. A sensitivity analysis is applied in varying the values of the parameter which were determined to have crucial influence on the sustainability of a district heating network operation.

The final discussion aims at providing information on how district heating can continue to be a currently widely accepted technology with a large fuel and cost saving as well as a considerable decarbonization potential. It leads to the conclusion that even though prospective heat demand patterns lead to the necessity of changing operation concepts, DH can still be a preferable technology.

STATUTORY DECLARATION

I hereby declare that I have authored this thesis independently, that I have not used other than the declared sources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Freiburg i.Br., January 7th 2013, ______________________

Preface

The present report is written as the Master's Thesis by Jannis Klonk, student of the Master of Science study program 'Sustainable Energy Planning and Management' at Aalborg University in Denmark.

The project was conducted during the period of September 1st 2012 to January 10th 2013, under the supervision of the external Associate Professor Anders N. Andersen. It was written within the company badenova WärmePlus which is a subsidiary company of badenova – an enterprise exclusively owned by communal shareholders (badenova.de, 2012). badenova is the largest water and energy provider in the region of South-Baden, in Germany and can be seen as a pioneer enterprise within the energy sector, dealing with the importance of an overall energy transition, shifting away from a system based on conventional power sources with high demand values, towards a more efficient system with increasing shares of renewable energy sources.

WäremPlus plans, constructs and operates energy conversion technologies for electricity, heat and cooling generation for individual buildings and district heating grids.

While the company, like its parent enterprise, pursues a business strategy focused on the three pillars of sustainable development (badenova, 2010, p. 1), the report aims at analyzing the current operation performance of various district heating networks, evaluating them on the basis of just this framework. Besides the issue of how to deal with a changing future heat demand is being discussed.

The author would like to thank all employees of the company badenova WärmePlus for offering the possibility to conduct the research within a real economic setting, particularly the following persons, who provided access to or direct information on their individual working sphere at the company:

Jörg Selinger, Sebastian Scheer, Martin Barnsteiner and Alexander Ripka, Egbert Wolf and Nadine Bleile

Special thanks shall be expressed to Klaus Preiser, head of badenova WärmePlus for enabling the project and to Anders N. Anderson for his supervision.

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Abbreviations

AGEB –	Energy Balance Working Group (AG Energie Bilanzen)
ASUE –	Association for an Efficient and Environmentally friendly Energy-Consumption (Arbeitsgemeinschaft für Sparsamen und Umweltfreundlichen Energieverbrauch e.V.)
BAFA –	Federal Office of Economics and Export Control (Bundesamt für Wirtschaft und Ausfuhrkontrolle)
BDEW –	German Association of Energy and Water Industries (Bundesverband der Energie- und Wasserwirtschaft e.V.)
BG –	biogas
BKWK –	Federal association of Combined Heat and Power (Bundesverband Kraft Wärme Kopplung)
CHP –	combined heat and power
DENA –	Federal Energy Agency (Deutsche Energie Agentur)
DECC –	Department of Energy and Climate Change (UK)
DSM –	demand side management
DH –	district heating
DHC –	district heating and cooling
DK –	Denmark
DN –	nominal diameter
EU –	European Union
EC –	European Commission
EnEV –	Energy Saving Ordinance (Energieeinsparverordnung)
EPA –	U.S. Environmental Protection Agency
ESTTP –	European Solar Thermal Technology Platform
GHG –	greenhouse gas
GIS –	Geographic Information System
GWh –	Gigawatt hours
HO –	heating oil
HP –	heat pump
IEA –	International Energy Agency
IINAS –	International Institute for Sustainability Analysis and Strategy (Internationales Institut für Nachhaltikeitsanalysen und Strategien)
IPCC –	International Panel on Climate Change

KEA –	Climate protection and energy agency Baden-Württemberg (Klimaschutz und Energieagentur Ba-Wü)
kWh –	kilowatt hour
LfG –	landfill gas
MWh –	Megawatt hour
MWi –	Ministry of Economics (Ministerium für Wirtschaft und Finanzen)
NG –	natural gas
OECD –	Organization for Economic Co-operation and Development
O&M –	Operation and Maintenance
PN –	nominal pressure
RD&D –	Research, Development and Demonstration
RE –	renewable energy
REA –	Renewable Energy Act
REH –	renewable energy heating
RES –	renewable energy source(s)
Rt –	return temperature
St –	supply temperature
TAB –	technical connection regulations (technische Anschlussbedingungen)
UBA –	Federal Environment Ministry (Bundesministerum für Umwelt)
UM Ba-Wü –	Department of the Environment of Baden-Württemberg (Umweltministerium Ba-Wü)
WCh –	wood chips

„The energy transition is the greatest economic challenge of the Federal Republic of Germany following reconstruction and the greatest eco-political challenge altogether".
(BMU, 2012 b, p. 8)

1 INTRODUCTION

Since the times of industrial revolution in the 18th and 19th century, the world has experienced an ever growing population, as well as a rapid growth in energy consumption. And numbers are still increasing. While estimations of the Organization for Economic Co-operation and Development (OECD) state an 80% higher world's energy demand in 2050 (OECD, 2012), an EU report on European's future energy demand expects a 4% growth (between 2005 and 2030), if current trends are persisting (Capros, et al., 2010, p. 24). The International Panel on Climate Change (IPCC) estimates a total increase of greenhouse gas emissions between 25% and 90% until 2030 (compared to 2000 levels), with energy related GHG emissions being the ones growing most rapidly (2007b, p. 111f).

When looking at current decisive issues connected to energy consumption, like depleting conventional energy resources, as well as limited access to renewable energy sources, dependency on politically unstable regions, resulting in rapidly rising fuel prices, environmental degradation and climate change, the mentioned figures as well as the fact that 85% of our planet's current energy consumption is based on fossil fuels (OECD, 2012), show the gravity of the situation.

The International Energy Agency (IEA), among others, keeps on emphasizing, that today's still rising investments in fossil fuel driven technologies will lead to a "lock-in" situation for the years to come, and "that the slow progress in environmentally friendly energy technologies is alarming" (IEA, 2012 a, p. 3). Research, Development and Demonstration (RD&D) investments in the energy sector have been lowered from about 20% in 1980 to below 4% in 2010, within IEA countries (IEA, 2012 a, p. 3).

1.2 REDIRECTING TRENDS

In spite of these facts and figures, a lot has been done in order to redirect current trends on all institutional (political/economical/societal) levels.

With the Rio Declaration on Environment and Development of 1992, the subject of sustainability came into focus of society (UNEP, 2012). For years the mentioned issues have often dominated the national as well as international political debate, with greenhouse gas emission being in the focus (IEA, 2009 (b)).

Within the climate and energy package the EU has released various directives for more sustainability concerning the energy future. It promotes the so called 20/20/20 target, which includes a 20% reduction of both GHG emissions as well as energy consumption, and a prospective 20% share of renewables in the energy sector until 2020 (EC, 2012 b). For the future the Energy Roadmap 2050 of the EU outlines an energetic pathway towards "a competitive low-carbon economy in 2050" (EC, 2012 a).

Concerning German national efforts, a total of 14 laws, support the transformation of the energy system; issued within the "Integrated Energy and Climate Program" (BMU, 2007 b).

1.3 HEAT CONSUMPTION WITHIN THE DISCOURSE OF THE ENERGY TRANSITION

In the media as well as in most of the political discussions concerning energy topics electricity supply and demand are the dominating issues. Heat- and cooling consumption do not appear to be equally important. This impression is confirmed when looking at present energy research. While the electricity market has largely been analyzed in several studies, this has hardly been accomplished for the heat market (Connolly, et al., 2012, p. 1). According to Frédéric Hug, President of Euro Heat & Power, an international association for district heating and cooling (DHC), not more than 4% of energy research is devoted to heating (Hug, 2012), despite the fact that heat is the energy form with highest demands (IEA, 2011, p. 11).

In Germany heat supply is responsible for about 25% of the end energy consumption, and even accounts for about 70% of the residential energy demand (Tzscheutschler, et al., 2007, p. 13). Considering these numbers it is obvious that heating is an essential issue in regard to the political commitments mentioned above; providing great opportunities for each of the three pillars of technological change: efficiency improvements concerning energy generation, energy savings on the demand side and substitution of fossil fuels by renewable energy sources (RES).

Depending on the local setting, German efforts today are being focused on demand side management (DSM) measures, like insulation activities, followed by an efficient and growing renewable supply of the remaining demand. Besides the mentioned legislative framework, progressive technological improvements and innovations support the slow shift from a preliminary fossil fuel based, towards a system with greater shares of RES.

In order to support decisions in forward-looking infrastructure investments, the first pre-study for the Heat Roadmap Europe 2050, issued for Euro Heat & Power by the two Danish universities of Aalborg and Halmstad, aims at providing an “optimal policy choice between insulating buildings and systematically using waste-heat”, as the temporary EU Energy Roadmap “omits a thorough analysis of the heating and cooling sector” (Connolly, et al., 2012, p. 1).

1.4 FOCUS ON DISTRICT HEATING

District heating (DH) is said to be a “key technology” for the achievement of energy security, economic development as well as on environmental protection (IEA, 2012 c). For being a mature technology, DH has contributed to major GHG reduction in many countries (IEA, 2012 b; Connolly, et al., 2012; Zinko, et al., 2008). It facilitates the consumption of waste heat, linking heat sources with heat sinks. Moreover it is an “extremely flexible technology which can utilize any fuel- including the utilization of waste energy, renewables and, most significantly, the application of combined heat and power (CHP)” (IEA, 2012 b). It does not only contribute to lowering GHG emissions but can also support the achievement of energy saving targets and contribute to a balancing of intermittent renewable electricity sources.

In Europe 5000 DH systems are existent, delivering heat to millions of consumers (4DH, n.D., p. 1). In Denmark, a leading country in the application of DH technology, the main driving motives for the development of DH had been fuel shortages during the Second World War and the oil crisis in the early 70s. Since then the country has become the leading nation investing in DH technologies. Besides systematic building insulation measures, an expansion by more than 50% of DH, largely based on CHP units, has contributed to 30% lower heat energy demand in

Denmark between 1972 and 1996; furthermore, fuel sources could be replaced in high quantities, even though heated space has increased by 46% (Andersen & Lund, 2007, p. 289). While DK already covers over 50% of its electricity by CHP (Andersen & Lund, 2007, p. 289), the German government aims at a 25% share until 2020, with numbers today being about 15% (UBA, 2009, p. 114).

Despite this, the operation of DH networks also faces difficulties, as not all locations are suitable and sources disagree on the fact, if DH can play an important role in the future energy provision. Wolf & Jagnow (2011) or Zinko et al. (2008) for example point out that future heat demand will often be too low for DH to be cost effective, as “initial investments are rather high” (Zinko, et al., 2008, p. 1) and low sales will often not offset the costs (Wolff & Jagnow, 2011, p. 9).

Besides these rather critical studies, several international organizations like the IEA or EuroHeat and Power, as well as a lot of research groups have been dealing with future energy systems and the question of how to guarantee future competitiveness of DH (e.g. (Lund, et al., 2010; Olsen, et al., 2008; Persson & Werner, 2010))by minimizing thermal losses (e.g. (Bøhm & Kristjansson, 2005; Dalla Rosa, et al., 2011)), or figuring out other options for the optimization of DH systems (e.g. (Knierim, 2007; Zinko, et al., 2008)).

The company badenova WärmePlus, which is the operator of about 160 heat generation units, supplying about 30,000 households with heat also has to deal with decreasing consumption values, facing new challenges for an optimized grid operation. The research at hand aims at isolating factors which affect a sustainable operation of current as well as future DH networks. In doing so a focus is laid on the overall network performance.

1.5 RESEARCH QUESTION

In asking the following research question, several parameters shall be isolated, which facilitate the evaluation of existing as well as the decision making process on prospective DH grids:

What are the determining factors influencing the cost-effectiveness, environmental compatibility and consumer’s acceptability of current and future district heating grids of WärmePlus and what measures can enhance profitability?

In order to answer this main research question, three sub-questions were developed. These shall guide the research, presenting a thorough understanding of the overall framework.

1. What is the current political and technological status quo influencing the utilization of sustainable heating systems and what are limiting factors for the utilization of DH?
2. What is the current performance of existing district heating networks of WärmePlus and what would be the costs for WärmePlus and its consumers of investing in optimization measures?
3. What are political and technological best practice examples and scientific advises supporting a sustainable network operation?

Before introducing the applied methodology which describes the applied theories and research tools used to tackle these questions, a determination of the study's limitations shall be given.

1.6 LIMITATIONS

The topic of district heating, also within the limits of the research question is very diverse. Some issues needed to be excluded or could only be dealt with briefly, leaving room for further analysis. The following describes the limitations which guided the research.

- While the issue of sustainable performance of heating systems covers a wide range of spheres – from fuel extraction or generation and acquisition, over heat generation to energy transmission and final consumption. A DH network operator has to deal with all of these issues. The main concern of the research however, is the overall grid efficiency with a focus on the network operation performance. This is the case for mainly two reasons; primarily this has been the major interest of WärmePlus and secondly, initial research showed that this concern is often neglected, while focus is laid on heat quantity rather than heat quality.
- While heat is demanded at various heat sinks – domestic customers, trade and industry – this report only covers the residential sector. Also waste heat of industrial processes will not be discussed, even though it might provide a great heat supply potential in the future.
- Also district cooling, often closely connected with district heating will only briefly be mentioned as a possible additional heat sink for the future (in terms of tri-generation).
- While CHP optimization offers a great potential for overall cost efficiency, the topic could only be covered theoretically. It is a complex issue, which requires the application of additional software tools and the inclusion of new input data, such as hourly weather and demand data, as well as information on the electricity market. The current framework regarding CHP operation is discussed, though.
- The analysis part of the study is confined by the availability of performance data.
- The investment calculations were based on a simplified network as the main aim of this section has been to display the influence of certain varying parameter, rather than presenting a final investment strategy.

2 METHODOLOGY

After having presented the background of current issues related to energy consumption, in particular to heat energy consumption and the role district heating can play within this large research field, this chapter shall elaborate on the research approach, the methodology and on the research tools which have been applied in order to answer the stated research question, as well as its sub questions.

2.1 CHOICE OF TOPIC

There were multiple impulses for this research topic. The initial one was the internship semester which was carried out at a department of badenova which compiles municipal energy and climate protection concepts. Here the special role of domestic heat demand and the issues relating to the multiple supply options within the overall energy system became apparent once again. Unlike industrial energy consumption e.g., which obviously also has a major influence on current and future energy demands, it is a topic closely related to the end consumer. Due to the fact, that 70% of residential energy consumption is related to heat, it can be influenced by each individual person by taking their decisions.

The fact that comparably few studies deal with the topic of heat has made this particular research necessary as well as interesting. Studies conducted by Wolf and Jagnow (2011) e.g., discussing limitations and design prerequisites of future district heating grids, also highlight the need of further applied research in this topic.

Finally the possibility of carrying out the research within a company setting, offering the possibility of analyzing real performance data, and dealing with concrete challenges a company faces within the framework of the pursued transformation of the energy system made it a valid research topic, requiring a holistic view of each pillar of the theory of sustainable development. *WärmePlus* is well aware of the fact, that some of the installations might not work at an optimum. Relatively high losses have been observed, however it has not been quite clear how much they differ from the losses appropriate to the installed technologies.

2.2 RESEARCH STRATEGY AND METHODS

Already in 1998, Engelmann and Krimmling (p. 16) have stated, that although the heat market could be regarded as being very attractive, there was a necessity to thoroughly optimize heat production costs, due to great competition. As this is still the case, and as there are ever stricter regulations going along with steadily decreasing demands, this study aims at analyzing grid performances of the company WärmePlus in:

1. highlighting some of the challenges the company faces;
2. emphasizing on grid specific optimizations and pointing out general advises for prospective investments; and
3. understanding consumer’s decisions.

By their nature the listed sub questions, supporting the analysis of the primary research question, require different theories and research methods, in order to be answered. Both qualitative as well as quantitative research approaches are carried out.

Being an applied research, that deals with substantial issues, regarding the operation of existing heat supply installations, as well as one important field of the energy transition, the project aims at presenting a profound analysis of influencing factors.

The complexity of this topic with its political, economic, technological, societal and environmental interrelations is obvious, for not only *WärmePlus* is being responsible for the installed facilities but also individual decisions made by consumers are of great importance.

While Table 1 lists theories and research methods applied for each research sub-question, Figure 1 illustrates the structure of the report. This is followed by a detailed description of the research methods.

Table 1: Applied theories and research tools

Sub-question	Applied theories and research tools	Chapter
1. What is the current political and technological status quo influencing the utilization of sustainable heating systems and what are limiting factors for the utilization of DH?	- Literature studies - Document analysis - Theory of sustainable development - SWOT analysis	5, 6, 7
2. What is the current performance of existing district heating networks of WärmePlus and what would be the costs for WärmePlus and its consumers of investing in optimization measures?	- Data collection and analysis - Arc GIS data processing - Excel: → Operation related calculations → NPV calculations	8, 9
3. What are political and technological best practice examples and scientific advises supporting a sustainable network operation?	- Literature Studies - Document analysis - Excel calculations	8, 10

2.2.1 *THEORY OF SUSTAINABLE DEVELOPMENT*

Without containing the keyword of sustainability, the research question clearly highlights the importance of focusing not only on the company's economic performance but rather on all three pillars defined by sustainable development. Therefore this principle shall be the guiding principle of the study and will be applied throughout the project. While giving a general introduction to the development of the sustainability concept, chapter 3 outlines its importance concerning operations of Wärmeplus.

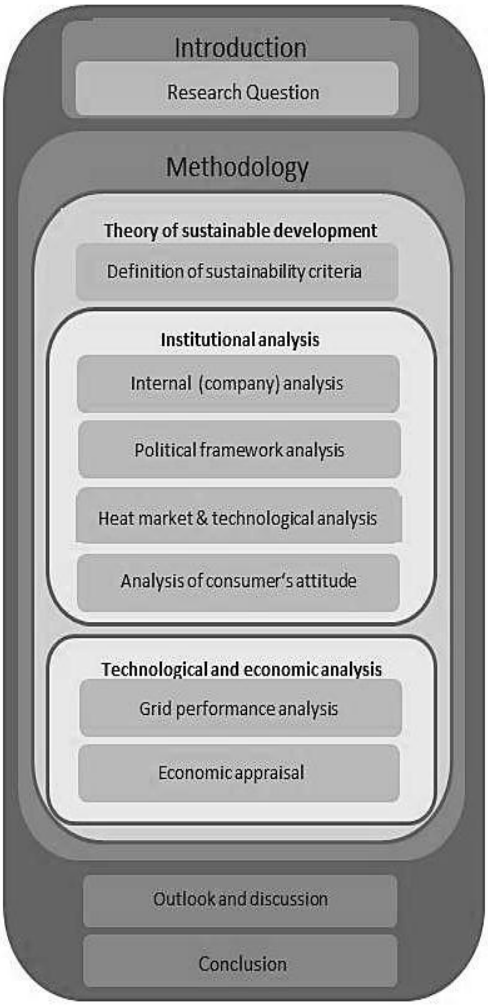

Figure 1: Structure of the report

2.2.2 LITERATURE STUDIES AND DOCUMENT ANALYSIS

Literature studies and document analysis have provided the major framework of the study, providing information about the political situation as well as technological advancements. Even though there is comparably little research on heat demand and supply in general and district heating in particular, when comparing the availability of research on electricity e.g., there is still a solid supply of various sources.

The legislative framework has grown over the last years. This has often been stipulated by politics on European level, but also by national or regional initiatives. Agencies and associations like the IEA or EuroHeat and Power e.g., have taken over responsibility to promoting energy efficient technologies, often based on RES and publishing a great range of studies and guidelines. Besides these two important sources, scientific papers, issued by individual scientist, have also been used to gain comparative data, as well as information on innovative developments.

In choosing the scientific literature, it was tried to get a balanced cross-section of all these interest groups, as presented in Table 2.

Table 2: Sources for document analyses

Knowledgebase	Role	Members / examples
Politics	Legislative framework; targets	EC / EU / federal and regional governments
(International) agencies, associations and other scientific sources	Think-tanks; Scientific background and advisory functions (RD&D)	IEA / EuroHeat and Power e.g.; Universities and other research institutes
Market players	Service provider and profit maximization	*WärmePlus* and other facility planners and operators; system component manufacturing companies
Consumers	Determining demand and installations (final decisions)	Final consumers

2.2.3 *INSTITUTIONAL AND TECHNOLOGICAL FRAMEWORK ANALYSIS*

In order to get an insight to the general setting in which the company carries out its business and in order to be able to define determining factors, a general overview of influential factors needs to be given. Following the idea of sustainability various sources suggest (Buchholz, et al., 2009; Terrados, et al., 2007) that besides only relying on demand forecasts and the search of an efficient low cost heat supply e.g., also environmental and social issues need to be analyzed, when carrying out research related to energy planning.

A multi criteria analysis was carried out based on the idea of a SWOT (Strengths, Weaknesses, Opportunities, Threats) Analysis, which originates from strategy and management planning theory. Looking at these factors has proven to be of great value for an initial understanding of the setting. Determining factors for a generally satisfactory operation of district heating grids clearly are based on multiple criteria.

The internal situation is looked at, focusing on strengths and weaknesses, as well as external opportunities and threats are regarded. The SWOT analysis theory has mainly been regarded as a guideline for the framework analysis providing a good opportunity to predetermine general spheres of influence on the performance of current and future DH grids and was not applied according to the exact proposed procedure as highlighted by Terrados et al. (2007, p. 1279) for example.

The external analysis includes a brief check-up on the political framework concerning thermal-energy issues and presents a general outline of the current situation on the heat market, and the prevalent and the consumption patterns and presents a technological and operational framework concerning DH (and CHP).

While external factors can hardly be influenced by the company's policies, internal factors can (at least) tried to be optimized. This part of the analysis presents certain key figures of the company WärmePlus in an initial step, and provides a basis for an in-depth understanding of the performance of chosen DH networks based on the technological framework analysis carried out before.

Apendix A presents all determined aspects, listed according to the mentioned categories.

2.2.4 DATA BASIS, ANALYSIS AND PROCESSING

In order to realistically evaluate the performance of the DH networks, detailed data on the total heat demand of each single customer, divided into the shares, hot water and space heat demand, ideally on a daily basis, would be needed. Also operation temperatures on a daily basis would facilitate the evaluation.

As only total values for fuel input and energy sales were obtainable, and operation temperatures were not available over a convenient timeframe due to automatic recording issues, specific scientific assumptions were applied. Loads and operation temperatures were simulated on the basis of the outside temperatures, which are recorded by the parent company badenova. Having defined temperature levels for maximum and minimum loads, as well as for maximum and minimum operation temperatures, the distribution follows a distinct gradient (described in chapter 7.1).

The two software tools Microsoft Excel and ArcGIS, developed by the company esri, were applied for data interpretation and processing. A GIS (Geographic Information System) software tool allows the interpretation and an understanding of interrelations of special data. In the present case it was mainly applied to extract information and visualize data of grid files, provided by RegioData, an external service provider which is in charge of all GIS based spatial data of badenova and badenova WärmePlus.

Aiming at providing valuable information for the company, effort was made for developing an Excel-tool which can also be applied for and support future grid evaluations. The tool was designed for being able to process available data as well as deriving performance values, in case data are not available. The data sources are mentioned in the chapters in which individual data are discussed.

The input sheet demands the following data:

- Outside temperature levels (on a daily basis)
- Total fuel input in CHP plants
- Total fuel input in boiler
- Approximate monthly distribution of heat demand
- Shares of combusted resources
- Total sales of thermal energy
- Total electricity generation
- Stipulated maximum and minimum operation temperatures (supply and return temperatures)
- Real operation temperatures on a daily basis (if available)
- Grid type, diameter and length (for each single segment)

For statistical evaluations, it can also process the following data, if available.

- Number of connected houses
- Total living space
- Total area of the supplied district

On this basis daily operation temperatures (if not available), shares of hot water and space heat demand, the volume flow and the specific thermal losses for each pipe segment and total emissions are determined in an initial calculation step. In a second step total and relative losses are determined on the basis of the provided information on the grid, leading to a potential discrepancy between the theoretically demanded and the effective fuel input (end energy). Figure 2 illustrates the example of the DH network ZO (Zentrum Oberwiehre in the city of Freiburg). The gap provides an obvious cost saving potential. On the basis of a sensitivity analysis it is aimed at a determination of the most likely operation temperature level, followed by a discussion on possible measures which can help to close the determined fuel input gap. Regarding this, another sheet in the Excel tool offers the possibility to determine the effect of theoretical grid renovation or substitution measures.

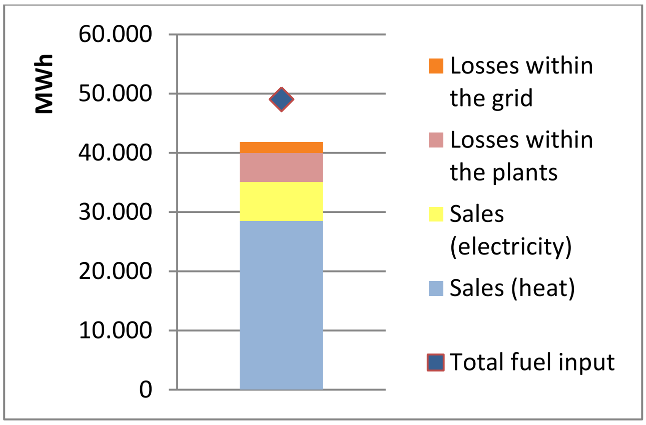

Figure 2: Effective fuel input (MWh) compared to theoretically demanded input, subdivided into sales and energetic losses

2.2.5 NPV CALCULATIONS

The investment analysis which is also based on Excel calculations, provides a practical framework for a comparison of different scenarios. Calculations have been done in order to determine whether saved energy levels could possibly offset investments in the grid (gird refurbishment measures). Another calculation compares investments in a DH network or individual boilers, with varying parameter, like level of heat demand, varying connection ratios, and varying operation temperatures.

It has to be made clear that calculations are simplified and do not cover each single technological component which would be needed to complete a network or an individual heating station. Nor do they cover varying investments in different heating units or fuels. The main aim of the calculations is to highlight the influence of varying parameters on the possible profitability of varying investments. The preceding technological analysis defines the above mentioned parameters as being of major importance for the grid evaluation.

In order to determine the feasibility of theoretical grid investments Net present Value (NPV) calculations need to be applied. These calculations include annual cash flows, including investment and operation and maintenance costs as expenditures. The incoming cash flows are comprised of the total heat sales. Figure 3 depicts the different cash flows.

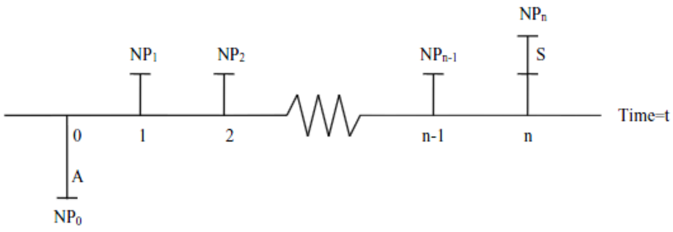

Figure 3: Decisive cash flows in a NPV calculation (adopted from (Lund, 2003, p. 5))

With:

NP_0 - as the initial investment cost

NP_n - as the yearly cash flows (sales minus costs)

n - as the project period and

S - as a potential scrap value, which is the remaining value of the installation after the investigated timeframe.

The formula for a NPV calculation is

$$NPV = NP_0 - S + NP_n \, x \, (\frac{1-(1+i)^{-n}}{i})$$

A NPV calculation is very much influenced by the set discount rate which displays the value of the lost capital “which could have been invested elsewhere” (Armitage, et al., 2002, p. 12) as well as the defined project period. The project period will be set to the approximate lifetime of most of the components which will be assumed to be 20 years, according to Wolff and Jagnow (2011, p. 41). In case of the grid, a lifetime of 30 years is assumed, leading to a scrap value which should be included in the calculations.

The project can be considered profitable if the NPV results in a positive value – the higher the more favorable. However, since the research question includes the question of societal acceptability, also a cost comparison for the consumers is carried out. While DH installations entail various advantages besides a possible economic incentive, the cost factor can be seen as the most important decision criteria, as described in chapter 7.5.

2.2.6 ANALYSIS OF NECESSARY CHANGE

The last chapter will briefly discuss necessary as well as possible changes on the societal, political and technological spheres. For the upcoming difficulties for DH networks within the alteration of future heat demand, the discussion will thus close the circle of the analysis, constituting some kind of outlook.

Concerning the social and the political pillars mainly hindering factors for a possible change are discussed, in introducing the theory of behavioral change, which basically states that people tend to trust in their habits, and that it is notoriously difficult to disrupt a socio-technological lock-in in these habits (Upham & Jones, 2012, p. 22). Changing people's consumption patterns usually needs to offer clear advantages. With other technologies of the modern world, like the car or the internet advantages are clear; with DH utilization advantages need to be clearly imparted (Zinko, et al., 2008, p. 85).

In highlighting the situation of Denmark, some policy proposals are presented which could provide the possibility of more acceptances towards efficiency measures.

3 SUSTAINABILITY ISSUES WITHIN THE HEAT PROVISION SECTOR

Before the internal analysis of the company and the external analysis of the political and technological framework, a definition of what is considered to be sustainable in the case of the present research will be approached.

The first distinct and clearly the most famous definition of sustainability until today was presented by the Brundtland Commission in 1987, five years before the Earth Summit in Rio de Janeiro in 1992, when the concept was published to the wider public. It depicts sustainable development as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The three levels of economy, society and environment should be incorporated (Brundtland Commission, 1987).

Many governments worldwide, as well as institutions and companies have long missed the chance to follow the path of a sustainable development. The German chancellor Angela Merkel sees men’s violation of this concept and it’s “addiction to utilize more of whatever resources, than we can afford” responsible for today’s major global crises (Federal Government of Germany, 2012, p. 19). Policy makers today are dealing with the fact, that “a reliable, economical and environmentally friendly energy provision is one of the biggest challenges of the 21st century” (Federal Government of Germany, 2012, p. 145); however, besides policy, this challenge concerns all societal levels.

As stated by the Commission, the concept of sustainability will always have a different focus, depending on the context (Brundtland Commission, 1987); however the three basic pillars of sustainable development have to be considered.

Like with all commercial enterprises, the primary concern of *WärmePlus is* to be able to survive on a market, which, in the case of the heat market has tightening regulations. The fact that the company is facing environmentally desirable decreasing heat demands shows that economic considerations are deeply interlinked with consumer’s and environmental desires. This has been recognized by formulating the company’s corporate Ecologic and Sustainability Guidelines which express badenova’s commitment (for the parent company, as well as for each subsidiary company) towards environmental protection and conserving natural resources as well as their sense of responsibility for climate change. Among others the company clearly commits itself to energy transition, in optimizing the relation between energy security, environmental compatibility and affordability, i.e. social acceptance (badenova, 2010, p. 1).

When deciding on planning and operating a network, the sustainability triangle must not be lost sight of. Due to its capability to lowering energy consumption, applying great shares of RES and rising energy efficiency DH is widely accepted as a technology contributing to these targets. This especially holds true for the application of CHP units.

Table 3 lists criteria for and effects of a sustainable application of DH grids, which will be dealt with throughout the study. Different heating technologies will have different effects on each of the three pillars. An optimal choice and an optimal performance have to be strived for, knowing about the alteration of the future market.

Table 3: Sustainability criteria for heat provision concepts / DH installations

Economic	Environmental	Social
- Because of high installation costs, O&M costs need to be predictable - Low vulnerability to fuel price fluctuations - Flexible fuels - Reliability including the possibility to distribute electricity - Competitive with alternative technologies - Application of storage technologies - Value added (e.g. Job creation and local resources)	- Demand reduction - RES - Energy efficiency - Minimized emissions (CO_2 and other particulates) and other environmental impacts due to constructions, fuel transport e.g. - Utilization of RES (within its limits) - Value added (local resources) - Application of storage technologies	- Reliable heat supply - Stable low prices - Easily manageable for consumers - Positive effect on health due to proper filters - Value added (e.g. Job creation and local resources)

4 INTERNAL CONTEXT ANALYSIS

The context analysis provides important information on the external framework which influences the prevalent investment climate and technological as well as operational optimizations of the company's heating systems. Before coming to the external factors, however, a short introduction to the company badenova WärmePlus shall be given here, briefly discussing the internal framework of the company.

The company badenova WÄRMEPLUS GmbH & Co. KG (hereinafter referred to as WärmePlus) is a subsidiary company of the badenova Gmbh & Co. KG which is the largest local water and energy provider in the region of South-West Germany. The parent company, which is exclusively owned by communal shareholders (badenova.de, 2012), was one of the pioneers dealing with the issue of the transformation of the energy system, shifting away from nuclear power and fossil fuels, towards a largely renewable system on the medium run. Since 2008 domestic customers have been supplied with electricity without nuclear power shares, and since 2011 even to 100% with green electricity. The total mix shall be shiftet to 100% renewable electricity within the coming years. With 600,000 natural gas customers, natural gas sales and distribution however remains their main pillar in the energy business. In Freiburg 80% of natural gas customers are supplied by badenova, in the black forest region about 30% (badenova.de, 2012).

For its pioneering role in the energy transition badenova has gained a reputation of not only being an energy provider but also an environmental service provider (badenova, 2011, p. 27). When following the local media this positive image has clearly gained acceptance, possibly leading to a competitive advantage in the region.

The work area of WärmePlus is the development, planning, construction and the operation of energy conversion technologies for electricity, heat and cooling generation and supply. Both, individual buildings and district heating grids are covered by the company's operations (badenova, 2011, p. 30).

WärmePlus which was founded in 2007, has 58 employees, covering working fields like plant and network engineering, plant operation and metering, energy procurement and sales, system support and maintenance, administrative work, etc. (badenova WärmePlus, 2012 b).

With a total of about 260 heat production units, between 37 kW and 43 MW (including emergency boilers), approximately 300 GWh thermal energy is delivered to about 900 connected buildings with roughly 50,000 customers. The thermal units consist out of more than 200 heating boilers and almost 60 CHP units, distributed over a total of 136 heating systems, providing heat via a total grid network of 59 km. 20 of the heating units are wood energy systems, one is powered by landfill and biogas. Additionally the company operates three heat pumping systems (badenova WärmePlus, 2012 a). Most of the plants have already been existent before the foundation of WärmePlus.

With a rather low share of annual turnover of 2.6% (badenova, 2011, p. 34) within the badenova group, WärmePlus has a considerable share of investments of 13.2% (badenova, 2011, p. 36). Considering the fact that sales were reduced due to a cancellation of a tax privilege for heat supply and a resulting economic deficit of certain plants as well as prospective decreasing heat demands, the expenses appear to be crucial (badenova, 2011, p. 32).

The mentioned positive image of the badenova group, for offering more and more efficient energy services and a considerable amount of renewable energy paired with the fact that DH offers clear advantages for the consumer and being a reliable and easily manageable technology. Moreover, offering a flexible future oriented fuel utilization, supporting local value added, the company constitutes a good basis for a prospective adaptability on the changing heat market.

Some challenges, however need to be overcome. To give an example, the current billing concept does not offer clear incentives for the consumers to comply with the stipulated contractual operation temperature levels e.g. For having a poor data basis of operational temperature levels, it is also difficult to confront the customers with the issue. This and other challenges, like CHP operation regulation for which better knowledge about heat demand fluctuations is needed, .are discussed in more detail in the analysis part of the report.

5 EXTERNAL ANALYSIS –HEAT RELATED POLICIES, TECHNOLOGIES AND DEMAND

This chapter shall present an overview of the current German energy policy, as well as the situation on the German heat market, and give an insight in DH technologies and important parameter needed in order to determine, whether a supply system can be regarded as a sustainable solution or whether certain measures need to be undertaken in order to achieve this.

5.1 ENERGY POLICY

Environmental conservation was introduced just before the Second World War; however it was not before the 1970s that environmental policy seriously became important (German Federal Agency for Civic Education, 2009). From then on Article 20a of the German constitution had established environmental protection in, stating: "*Mindful also of its responsibility toward future generations, the state shall protect the natural bases of life by legislation (...)*" (German Bundestag, 2010, p. 27).

Environmental legislation has been based on the following three important principles:

- The p*recautionary principle*, which demands minimal risks and emissions adequate to the technological state of the art,
- the p*olluter pays principle*, which determines, that the responsible person/organization for environmental hazards has to pay for remedial measures, and
- the c*ooperative principle*, which aims at a joint protection of the environment, by the state, the population and enterprises (BMU, 2012 a).

Being based on these basic principles, the federal legislation today is very much influenced by several European directives and laws. Concerning energy utilization, the European Parliament issued the so called Climate and Energy Package, in 2009. Mainly three directives are guiding the famous 20/20/20 target, in demanding its member countries to work out a national legislation, as well as to publish their achievements.

- With the directive on the promotion of the use of energy from renewable sources (2009/28/EC), the EU aims at a 20% share of renewables by 2020 (EU, 2009, p. 28).
- With the greenhouse gas emission allowance trading scheme (2009/29/EC) the target of a 20% GHG emission reduction shall be accomplished (UBA, 2011 b).
- With the energy efficiency directive (2012/27/EC), the EU reacts to the slow implementation of efficiency measures within the member countries to reach the target of reducing energy demand by 20% until 2020. It includes measures for energy conversion, energy distribution and energy consumption (DENA, 2012 (b)).
  Besides it highlights the 'untapped' potential of CHP combined with DH to save primary energy and proposes national assessments on the potential (EU, 2012, p. 5) and states that "Member States shall take adequate measures for efficient district heating and cooling infrastructure to be developed", if conditions allow a more efficient DH operation than other heating infrastructure, but costs would be higher (EU, 2012, p. 20).

Additionally there are the directives on the energy performance of buildings (2002/91/EC), on the promotion of cogeneration based on a useful heat demand (2004/8/EC), the directive on the energy performance of buildings (2010/31/EC), the directive on industrial emissions /2010/75/EC), only to give a brief overview about the fields of energy utilization, the EU is dealing with (europa.eu, 2011).

Generally, these directives stipulate that EU member countries have to issue national legislations, which guarantee the achievement of the EU targets. Article 10 of Energy Efficiency directive e.g. additionally aims at the development of local heat and renewable heat roadmaps.

The EU itself has published the Energy Roadmap 2050. One of its claims is the development of a smart heating infrastructure. With DH offering energy efficiency and the possibility to run on renewables, as well as being a very flexible system, it can meet these requirements. In addition to the Energy Roadmap, the Heat Roadmap Europe 2050 is being worked on right now, as the authors see the Energy roadmap being too focused on electricity issues alone (see (Connolly, et al., 2012)).

DH is not (specifically) covered by European legislation; still the mentioned directives on CHP as well as on building energy demand, industrial emissions, renewable energies and energy efficiency, etc. constitute an important framework for DH.

5.1.1 MOST IMPORTANT NATIONAL ENERGY TARGETS

As mentioned in the introduction the federal government of Germany developed the so called "Integrated Energy and Climate Program" in 2007 which lead to the issuing or redrafting of a total of 14 laws, aiming at an environmentally friendly, reliable and affordable energy provision. This goal shall be achieved by a profound modification of the energy supply, including a predominant utilization of renewables until 2050 (Federal Government of Germany, 2012, p. 143; BMU, 2007 b). One of the guiding targets is a 40% cut of CO_2 emissions by 2020 and 80 – 95% until 2050 compared to 1990. Even though there have been further political developments, this target has not been revoked until today (Federal Government of Germany, 2011 a).

While the government continued forming their future energy targets, in issuing the so called Energy-Concept 2050 in 2010 and agreeing on the lifetime extension of nuclear power plants., the nuclear disaster in Japan in March 2011 lead to the decision on a final nuclear phase-out until 2022.. From then on the energy transition has been considered to be the greatest challenge economic policy has to face. (BMU, 2012 b, p. 8). RES have finally been regarded as the future's most important energy source, aiming at a share of 35% of the electricity mix in 2020 and 80% in 2050. The building sector shall achieve a 20% heat demand reduction and a share of RES of 14% until 2020 and an 80% reduction of the primary energy demand and a heat coverage by a 100% share of renewables until 2050. Electricity consumption and total primary energy demand shall be lowered by 10% and 20% respectively until 2020 (Federal Government of Germany, 2011 a; Federal Government of Germany, 2011 b).

5.1.2 BRIEF LEGISLATIVE OVERVIEW

- The Renewable Energy Act (REA) is probably the most famous legislative framework, and has so far been the most important legislation promoting the energy transition, in contributing largely to incomparable growth rates in RE technologies (in terms of electricity). This act has already remained in force (with several amendments) for almost a decade. The predominant target is to achieve a 35% share of renewables in the electricity sector until 2020 and a 80% share until 2050.
  Due to a 10% own consumption, which has been decided on with the newest amendment of the REA, a decentral electricity production and direct consumption is promoted, aiming at a pressure relief on the high voltage grid (Wolff & Jagnow, 2011, p. 31).

- Concerning the issue of heat, the Renewable Energy Heating (REH) Act (of 2009) promotes and forces the application of renewables in the heating sector and also the development of DH grids (Wolff & Jagnow, 2011, p. 9). A 14% share of renewables has been set for the total heat market of 2020. The law forces property owners of new residential buildings to cover an over 50% share of their heat demand with renewables, unless certain substitution measures, like the utilization of CHP units, insulation measures, which lie above the required level, or the connection to a district heating grid, which again is partially fuelled by renewables or a CHP unit, are being undertaken. Property owners, who voluntarily exceed legal demands, concerning the share of renewables, are able to receive funding.

  The REH Act includes a regulation, which allows municipalities to dictate DH connection, if this supports climate protection targets by means of the utilization of RES, solar thermal energy, heat pumps or CHP units. It also allows regional governments to issue a legal framework for heat installations of existing residential buildings. In the case of the federal state Baden-Württemberg, an existing legislation of 2007 endures (v.i.) (DENA, 2012 (c)).

- The Energy Saving Ordinance (EnEV) of 2009 is also one of the many building blocks of German efforts towards a sustainable energy future mostly covering energy efficiency in houses, but also dealing with the expansion of renewable energy sources. It sets energetic minimum standards not only for newly constructed buildings, but also for existing buildings which carry out any kind of modernization on the cladding, sealing, roof, windows etc. Additionally it sets minimum efficiency standards for heating or cooling, as well as warm water distribution technologies and aims at a preferably quick substitution of old (< 1978) heating installations. The EnEV aims at an energetic improvement, leading to a 30% heat demand reduction, compared to previous building standards (DENA, 2012 (a)).

- With the release of the CHP Act in 2002 the government aimed at a stipulation of a technology which is able to produce heat and electricity simultaneously, leading to a much higher efficiency than individual installations ever could achieve (ASUE, 2012, p. 4).

  The law, which had its newest amendment in 2012, determines that the transmission system operator (TSO) has to guarantee a priority connection to the grid and lists a feed-in obligation. This is regulated according to §5 of the REA and also holds true if the grid needs to be optimized or improved in order to tolerate the connection. However the guaranteed feed in of the generated electricity only accounts for a total of 30,000 operation hours, with units above 50kW el and optionally ten years or 30,000 operating hours for units below 50kW el. The operator of the plant has to take care of electricity marketing by himself, choosing high priced periods for electricity generation and sales. During the first 30,000 hours an additional payment is guaranteed (ASUE, 2012, pp. 9-15).

In promoting the expansion of CHP units, the German government aims at a 25% share of electricity production until 2020. According to §1 this shall be the case in order to reach the energy efficiency targets, as well as climate protection targets set by the government (ASUE, 2012, pp. 14-16). In order to achieve this share, each year a total capacity of 2,700 MW needs to be installed until 2020 (UBA, 2009, p. 114).

Since 2009 the law has enabled DH grids to receive funding if heat (or cooling) is provided by at least 60% of CHP, and in 2012 the funding of thermal storage tanks was added as long as the predominant share of the produced heat is generated by a CHP unit. With this change CHP unit operators are encouraged to run their plants current regulated, thus enabling them to compensate for fluctuating RES in the electricity grid (BAFA, 2012).

Last but not least CHP plants need to be highly efficient. This again is defined by the European CHP directive (2004/8/EC), which states that CHP units have to be able to contribute to a total saving of primary energy demand of at least 10%, compared to separate production (ASUE, 2012, p. 8).

While the CHP Act determines the funding for a CHP investment as well as the feed in tariff for fossil fueled units (for the above mentioned hours), the REA lists the tariffs for renewably fueled CHP plants.

- As stated above, the federal Renewable Energy Heating Act allows regional governments to decide on heating standards for existing buildings. So far Baden-Württemberg is the only federal state, which has issued an additional law (the Renewable Heating Act of 2007), obliging owners of existing buildings to cover a 10% share of their heat demand with renewables when performing any kind of energetic refurbishment. With this a total share of renewables in the heat market of currently 8% shall rise to a 16% share in 2020. As with the Renewable Energy Heating Act of the federal government, substitution measures are allowed (UM Ba-Wü, 2007).

  In 2011 the regional government of Baden-Württemberg has additionally decided on a Climate Protection Act (which has not yet become effective) which shall stipulate county specific energy as well as GHG reduction targets. Until 2020 total energy consumption shall then be lowered by 19%, and the share of RES in the heating sector shall even rise up to 21%. Because 89% of GHG emissions of the federal state are energy related, the energetic sector is being focused the most (Schmidt, et al., 2012, p. 14). Figure 4 illustrates the overall targets, subdivided for each decade to come, until 2050.

- As mentioned above, an obligation for the connection to a DH network is possible in all federal states in Germany. Only in Bavaria this is limited to new construction areas and redevelopment areas. The prerequisite is that the construction is in the public interest and contributes to public health (air pollution limitation), or to the common goal of climate protection. In 2006, this option on obliging consumers has been approved by the Federal Administrative Court; however in reality it has hardly been practiced (UBA, 2011 a).

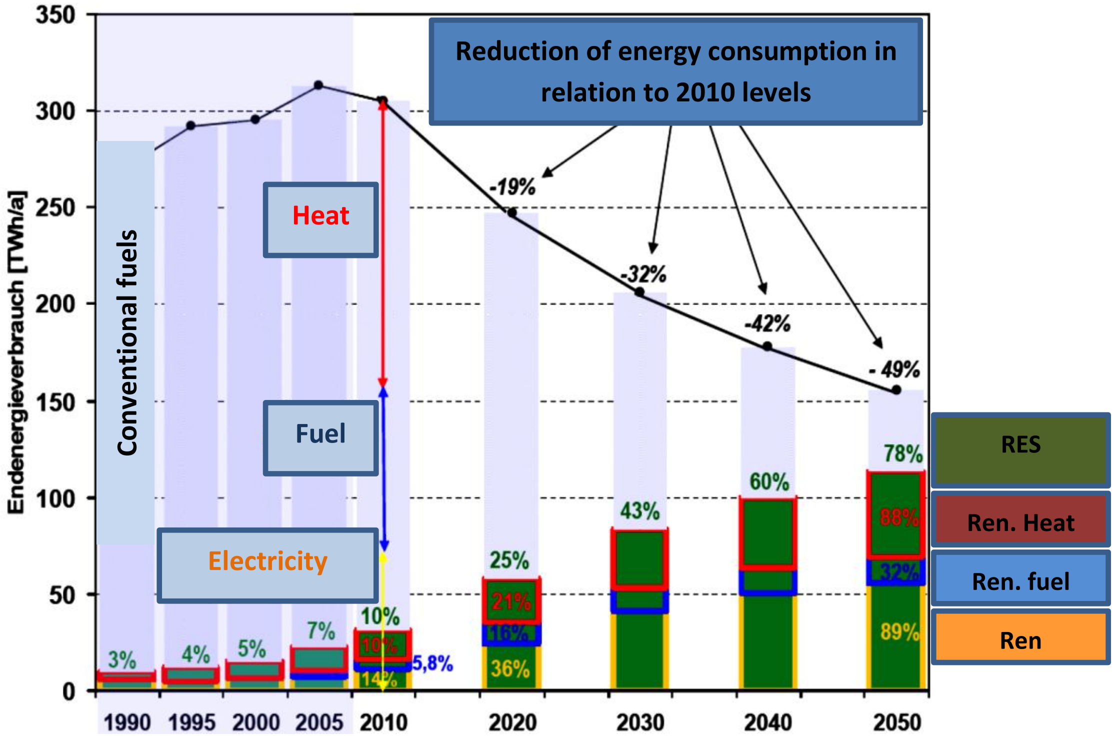

Figure 4: Energy Efficiency and RE targets of the planned climate protection act of Baden-Württemberg (based on: (Schmidt, et al., 2012, p. 1))

There are various laws, aiming at a sustainable development of the energy sector. Changing governments and thus a changing legislative framework, however can pose problems for companies, as they have difficulties to adjust to the political framework and the technological and demand side developments it entails.

At the end of the study, the practicality of the laws will be discussed, on the basis of the grid evaluations and the discussion about future challenges. It will also be discussed if the legislative package is sufficient or if some areas like certain barriers need to be tackled as well. Besides the subsequent technological evaluation, the political framework does pose substantial influence on the applicability and sustainability of the DH technology.

Before coming to the description of key parameter of the DH operation and the grid evaluations, the external framework analysis is continued with an introduction of the status quo of the current heat demand and its likely future trends, as well as with a description of the currently applied supply technologies and resources.

5.2 HEAT DEMAND CHARACTERISTICS

For the last decades, the German heat market has been characterized by steady changes in demand and supply, for both, resource developments or political regulations.

When planning any type of heat supply concept for a certain district present and possibly future consumer data need to be obtained. While electricity demand e.g. is comparably constant throughout the year, having daily fluctuations but not large seasonal fluctuations, heat demand differs a lot depending on the season. Another huge difference is that electricity needs to be produced the moment it is demanded and is rather difficult to store; thermal energy can be stored comparably easy, having the effect, that load peaks can be covered by the storage tank which again leads to a smoother plant operation and in the case of CHP to the option to be run current operated (Knierim, 2007, p. 56).

As mentioned in the introduction, heat energy demand sums up to more than 25% of Germany's total energy demand. Within the residential sector it is even responsible for about 70% (Tzscheutschler, et al., 2007, p. 13). There are many central or decentral technological, as well as operational opportunities, which can be chosen to meet this demand, depending on consumer's preferences but also lead by fuel price developments, as well as by courses set by legislation.

The heat load is mostly influenced by energetic standards of the building, outdoor temperature, as well as consumer's behavior ('social component') (AGFW, 2012 (b), p. 27) and consists of hot water demand as well as space heating demand. Within residential complexes, the almost constant warm water demand is characteristic, mainly influenced by the number of residents (AGFW, 2012 (b), p. 27), or by approximation by m^2 (Hausladen & Hamacher, 2011, p. 21); however the ratio of space heat and hot water demand is changing throughout the year. While space heating demand has been decreased and will further be reduced by demand side management measures, the latter one will stay almost unchanged (Dötsch, Taschenberger, & Schönberg, 1998, p. 5). This is illustrated by Figure 5, which depicts different energetic standards for space heat demand in the winter season, and a stable hot water demand independent from the housing standard during the summer months.

According to Hausladen and Hamacher (2011, p. 25) the cycle of refurbishment of a residential building is about 45 – 65 years. When considering the future heat demand of an area, it has to be kept in mind, that after this period (the latest), an often drastic decrease of heat demand takes place, as buildings will be adjusted to time specific regulations. The author's Energy Utilization Manual presents figures for the specific heat demand for different building categories and building age classes as well as for the deductions due to insulation measures (Hausladen & Hamacher, 2011, p. 20 & 107). These values are applied in the chapter 9.2 where the heat demand of an imaginary district with varying demand values is modeled and the cost effectiveness of possible supply options is compared.

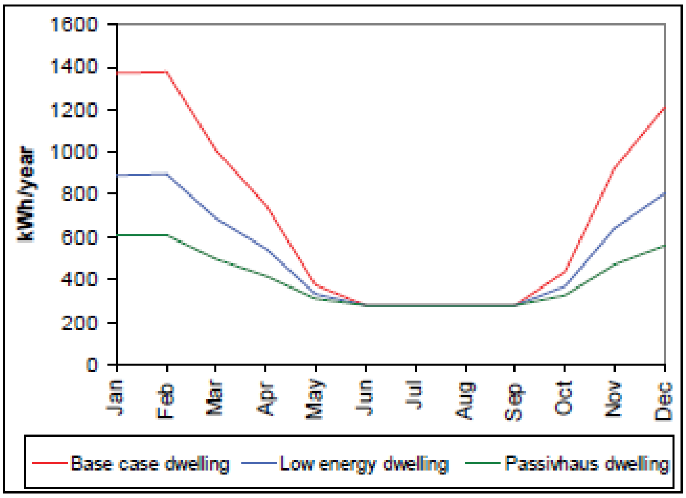

Figure 5: Thermal load for three different building classes (adopted from (Wiltshire, 2011, p. 92)) – the demand corresponding to a flat of about 100 m²

Having knowledge about the building type and age and with access to a ground plan and knowledge about the number of floors, the heat demand of a building can be determined by the following formula:

$$\begin{aligned} &Total\ heat\ demand\ per\ building \\ &= \left(\frac{specific\ heatdemand}{m^2 a} + \frac{specific\ hot\ waterdemand}{m2\ a} \right. \\ &\left. - \frac{reduced\ demand\ due\ to\ refurbishment}{m^2 a}\right) * total\ floor\ space\ (m^2) \end{aligned}$$

with heat demand in kWh and total floor space derived by the total ground plan in m^2 multiplied by the number of floors and by 0.8.

With regard to this, it needs to be mentioned that ¾ of the German building stock was constructed before the first Ordinance on Thermal Insulation, issued in 1979 (Federal Government of Germany, 2012). While this effect needs to be kept in mind when planning and dimensioning a heating grid and the heat generator, as profitability can depend on future demand developments, plants obviously need to be able to cover the current heat demand with first priority (AGFW, 2012 (b), p. 27).

Figure 6 presents the development (in Germany) of the total space heat demand per capita (black), which is dependent on the space heat demand per m^2 (rose) and the living space per capita (yellow curve). It becomes obvious, that the total space heat demand per person will not decline dramatically as the demanded living space will most probably continue to grow; however its distribution will be quite different in the future.

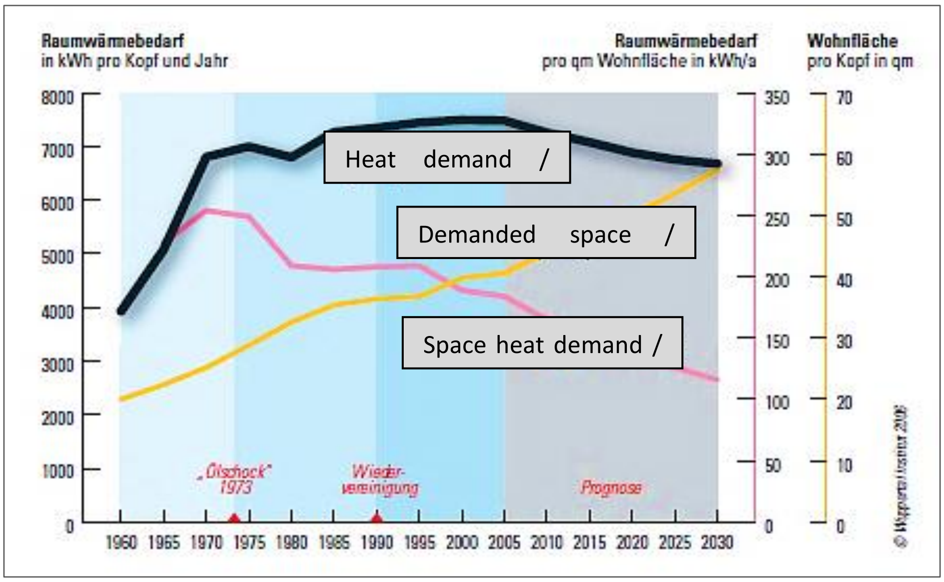

Figure 6: Development of space heat demand (per capita and m²) and living space (per capita) (adopted from: (BMU, 2007 a))

As a side note it shall be mentioned that in order to be able to estimate the heat demand for non-residential buildings, it is necessary to differentiate between industrial buildings, office blocks, schools, hospitals etc. and to classify the ratio between space heat and hot water demand as well as its distribution over the year, as this is very different to the heat demand of the building sector (Dötsch, et al., 1998, p. 11).

5.3 HEAT SUPPLY IN GERMANY

Numbers of 2004 state, that 85% of the consumed heat in Germany accounted for the residential sector (IEA, 2007, p. 159). Today, heat demand of newly constructed residential buildings in Germany is covered by 50% by individual gas boilers, by 23% by heat pumps and by 16% by district heating; leaving the extra 11% to biomass, solar heating, electricity and fuel oil. Within existing buildings, gas boilers also cover about 50%, fuel oil 30%, district heating 12.6%, and biomass together with solar heating and heat pumps only about 3% (AGEB, 2011, p. 1.09f). Figure 7 illustrates these figures and presents an obvious shift away from fuel oil, which in the 1990s still had, together with natural gas, a total share of over 75% in the existing buildings.

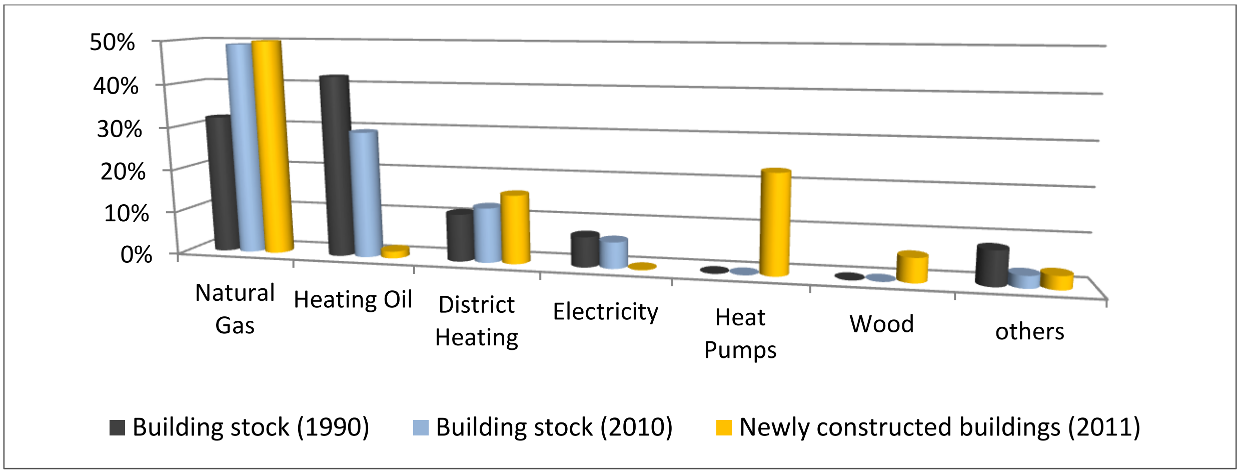

Figure 7: Fuel distribution for heating in Germany – existing (1990, 2010) and newly constructed buildings (based on: (AGEB, 2011, p. 1.09f))

Even though renewables have been covering low shares until today, and most of it is covered by biomass (94%), solar thermal and geothermal markets have shown growth; in the case of solar thermal, however the total contribution has only be only 0.2% in 2006 (see Figure 8) (IEA, 2007, p. 159).

The annual potential of biomass consumption lies at about 15-18% of current heat demands, if half of the total biomass potential would be utilized for heat provision. Wolff and Jagnow (2011, p. 19) express the theoretical potential in 30 – 35 kWh/(m²a). Today newly constructed buildings consume about 70 – 80 kWh/(m²a). Considering the target of the federal government of covering all domestic heat demand by renewables by 2050, it gets clear that other RES need to be applied in higher quantities as well.

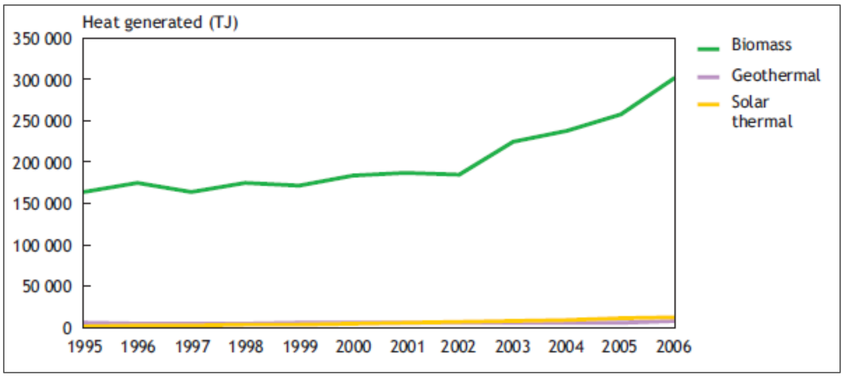

Figure 8: Historic growth of RES in the German heating sector (adopted from (IEA, 2007))

As illustrated by the ESTTP (European solar thermal technology platform) (2007, p. 22), solar thermal installations will potentially have substantial growth in the coming years. Figure 9 depicts its potential growth, if some political advancement is going to take place. Still today most installations only cover a share of the hot water demand (usually 40-60%); combined systems are gaining more importance, though (IEA, 2007, p. 159). With continuing decreasing demands the ESTTP even assumes that solar thermal installations can cover up to 50% of the future heat demand in Europe in the long term (ESTTP, 2007, p. 21). The role solar thermal appliances can play in future DH networks is briefly discussed in chapter 10.3.2

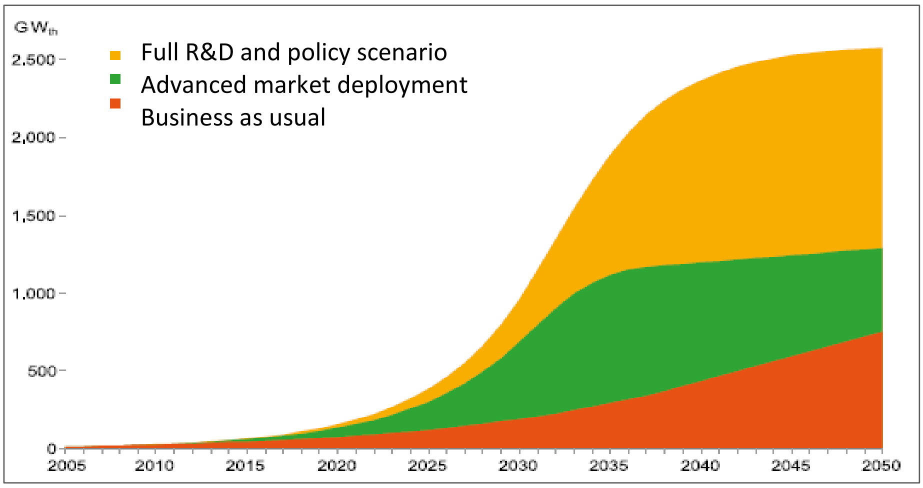

Figure 9: Potential growth of solar thermal installations according to three different future scenarios (adopted from: (ESTTP, 2007, p. 21))

In 2003 the share of DH in residential buildings amounted to 13.7%. In the federal states of Eastern Germany, the share was considerably higher than in the western part (32% to 9%). In 2011 a total sum of 1,400 grids, with a total length of about 20,000 km have been installed. More than 50% of energy providers (550 out of 1,000) operate DH-grids (UBA, 2011 a). While the total grid length is growing (see Figure 10), the amount of delivered heat has been decreasing over the last decade (Wolff & Jagnow, 2011, p. 16).

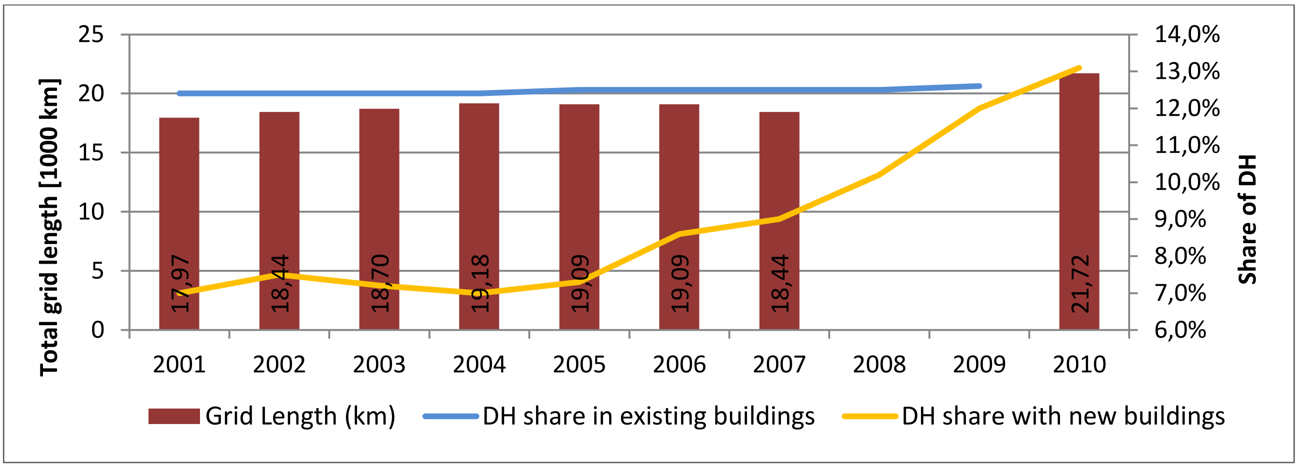

Figure 10: Total German DH grid and share of connected residential buildings (based on: (BDEW, 2010))

Central or decentralized heating systems have different advantages: An economic heat supply can only be achieved by an appropriate mix (Wigbels & Nast, 2005, p. 106). If a DH network is only producing heat, it is in direct competition with a decentralized installation (given the fuel is the same). Wolff and Jagnow (2011, p. 11) point out that the efficiency for small sized individual installations could be improved significantly during the last years. The authors insist that central installations can only be justified if the efficiency gain of a DH network can compensate the losses caused by the grid (described in chapter 7.2). This claim goes in line with the efficiency definition of the EU, mentioned above.

In order to achieve this efficiency advantage, 83% of the European heat demand which is covered by DH (12% within the EU27) is generated by CHP units (UBA, 2011 a). 2/3 of these again are still being powered by fossil fuels (Connolly, et al., 2012, p. 17). Figure 11 presents some chosen European countries, illustrating that distribution is very divers. Scandinavian countries have obviously earlier seen the potential of DH, than other countries in Europe. Reasons for this success are mentioned in chapter 10.2 where potential political progress is discussed which would support future technological advancements, and thus applicability.

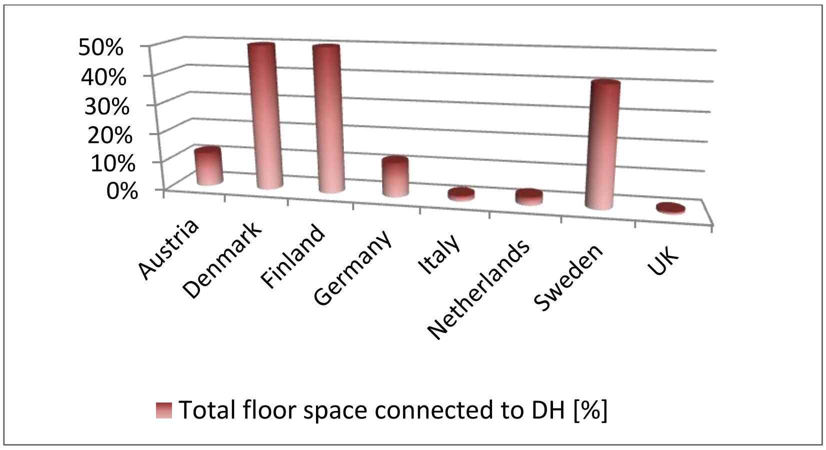

Figure 11: DH saturation in selected European countries (based on: (Zeeg, 2010))

As mentioned before, CHP plants provide, besides the general benefit of total efficiency gains, the opportunity to balance fluctuating RES within the electricity system. Germany aims at a total electricity share of CHP units of 25% by 2020. While the total electricity generation by CHP plants has been increased by 22% between 2003 and 2010, its share today does not exceed 16%, especially as the total electricity consumption has, contrary to all efficiency targets, still been growing by 8.5% (UBA, 2012). As can be seen in Figure 12, expansion of these plants needs to be accelerated, in order to achieve the aspired target. While CHP operators already face difficulties in running their units profitably, because of low electricity prices due to large shares of RES, the lately amended CHP Act, still has to show, whether it can contribute to this development. This issue is also taken up again in the above mentioned chapter 10.2.

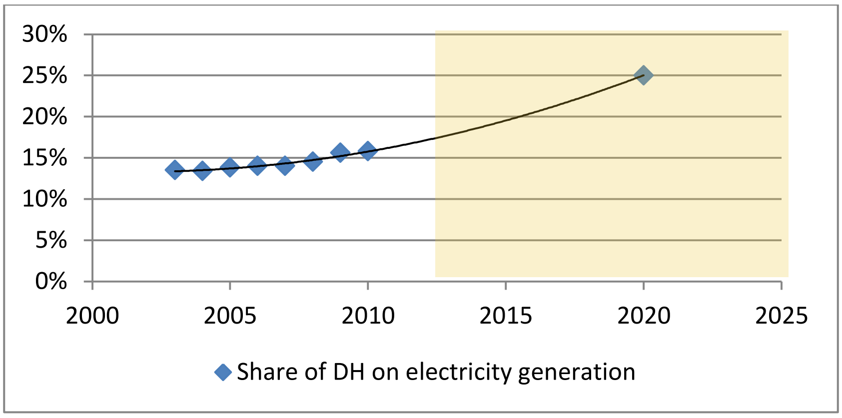

Figure 12: Share of CHP within the German electricity mix, today and in the future (based on: (UBA, 2012)

For the future, political targets, like emission reduction and efficiency improvements, as well as fuel price developments will have considerable effects on the heat demand as well as on a the chosen supply technologies and fuels. In this regard also waste heat of industrial processes will probably become more interesting. Regarding DH its fuel flexibility (also the possible utilization of this process heat) can be an important future advantage.

Having described the external circumstances, influencing heat demand and -supply, as well as the status quo of the German heat market, technological and operational aspects of DH are introduced. In the introductory part of the chapter, other distinct characteristics and potential advantages of the technology are going to be discussed.

6 TECHNOLOGICAL ASPECTS OF DH

A rough definition of DH is given by the association for an efficient and environmentally friendly energy provision (ASUE, 2012, p. 24). They describe it as an installation for a grid-bound heat provision, having a horizontal expansion across property boundaries of the grid supplying heating unit, and having an undefined quantity of connected customers, with at least one not being the owner or the operator of the heating plant.

Like other energy networks, DH grids are expensive to install, with incomes being distributed over many years. The system can only be viable, if there are sufficient subscribers, who are willing to connect. The supplier will be a monopoly supplier, which implies, that customers need to trust the operating company, that the tariffs represent fair costs; however this will be guaranteed via the contract. Knierim (2007, p. 56) points out one crucial difference between electricity, fuel or heat supply: for being a circulating system, the heat transport medium comes back to the power generating unit; and with it the residual energy in the return flow, which is very much influencing the operation quality. Another difference between heat and electricity is that heat needs to be consumed close to the thermal plant; however it can be stored with far less expenditures (IEA, 2011, p. 10).

The very first (similar to today) DH systems were introduced in the 1880s in Europe and the USA. Until 1930 the usual energy carrier of the first DH generation was steam. The second generation of DH systems, which has been applied until the 1970s, then changed the energy carrier to pressurized hot water, using supply temperatures often over 100°C. During the 1980s, the third generation finally “took a major share of all extensions” (4dh.dk, 2012, p. 2f), and until today pressurized water is the most utilized energy carrier, now having supply temperatures below 100°C. However, a fourth generation DH system is about to spread, aiming at lower and more flexible supply temperatures, as well as more flexible materials, in order to achieve a “more environmentally, customer-orientated solution” (Euroheat & Power, 2012, p. 8).

This so called 4th Generation DH system will be approached in chapter 8.3, where prospective solutions to current and future technological challenges are introduced and applied in calculations. The chapter at hand as well as the subsequent network analysis mainly deals with third generation DH networks, for these being the ones applied by WärmePlus until today.

For its capacity to lower primary energy consumption, which especially holds true for CHP powered DH grids, the Federal Environmental Agency (2011 a) points out its great potential contribution to climate protection; which for a company like WärmePlus cannot be the only investment incentive for obvious reasons. While one prominent German DH pipe producer states that DH is “an integral part of our modern understanding of a rational and sustainable use of energy” (isoplus, 2012 a), different scientific sources, (e.g. (IEA, 2009, p. 95; UBA, 2011 a; BINE, 2009, p. 1; Armitage, et al., 2002)) agree on the following additional advantages of DH:

- Possible large scale integration of RES (e.g. biomass), with larger facilities having lower specific investment costs than the same capacity installed by individual boilers.
- More economical exhaust gas cleansing of some RES, as this complex and expensive process is cheaper on large scale as well.
- Possible utilization of local excess heat of electricity production or industrial processes which would otherwise be wasted or possible exploitation of larger geothermal deposits.
- Possible application of large thermal storages, which can contribute to higher operation efficiencies, as they level out the operation and reduce large operation fluctuations, and which can level out temporal fluctuations of thermal availability (e.g. solar thermal).
- Potential dependency reduction on imported fossil fuels.
- Improved security of supply and local job creation potential, as well as increasing local added value.
- Possible GHG emission reductions.
- Potential stabilization of the electricity network – if powered by a CHP unit.
- Guaranteed fixed prices over the year for the consumer, without sudden operation and maintenance costs.
- Avoids need for own boiler, and leads to a gain of space, and to lower connection costs.

Among all these potential advantages, the Heat Roadmap Europe determines DH's main functions as fossil fuel substitution and CO_2 reduction, as well as primary energy demand reduction, in focusing on the two pillars of heat recycling, and renewable energy expansion (Connolly, et al., 2012, p. 17).

Besides the mentioned supporters for DH, there are also several critical voices. Wolff & Jagnow e.g. (2011, p. 10) state that DH gets dispensable, as soon as there are individual options which can contribute to a simultaneous energy conversion, working with the same efficiency as in a heat network. Their study concludes that this fact is getting more likely with heating demands dropping rapidly in the future. The report at hand aims at analyzing whether there are measures, which preserve the listed advantages, compared to other heating solutions.

6.1 THE DH GRID

The very first (quite obvious) criteria for the connection to a heating grid, is either the availability of an existing nearby network, or the possibility of its construction; the latter one depending on various factors, which are discussed in chapter 7, where general factors are presented and in chapter 0, where these factors are applied and evaluated, based on real performance data of existing DH networks of *WärmePlus*.

The total system of a heating network consists of the heat source, the distributing grid and the consumer interface (the building units). Therefore, in order to plan district heating grids, the technical dependencies and interrelations between the phases heat production, -distribution and -consumption are to be considered. The combining and essential parameter of these three units is the supply- and the return temperature. In order to optimize the system, the qualitative and quantitative influence of these temperatures needs to be understood and will make up the principal focus of the analysis in chapter 0.

Figure 13 illustrates such a system, which in this case is powered by a CHP unit. The energy carrier is is distributed from the heat source to the customer's substation via supply pipes and is returned after heat has been extracted. This circulating system is driven by pumps which "generate a pressure differential between the supply and return pipes" (IEA, n.D., p. 57).

There are several insulation standards of the pipes, different diameters, and single or twin pipes. These parameters are described in chapter 7.2, where their roles are being analyzed as well.

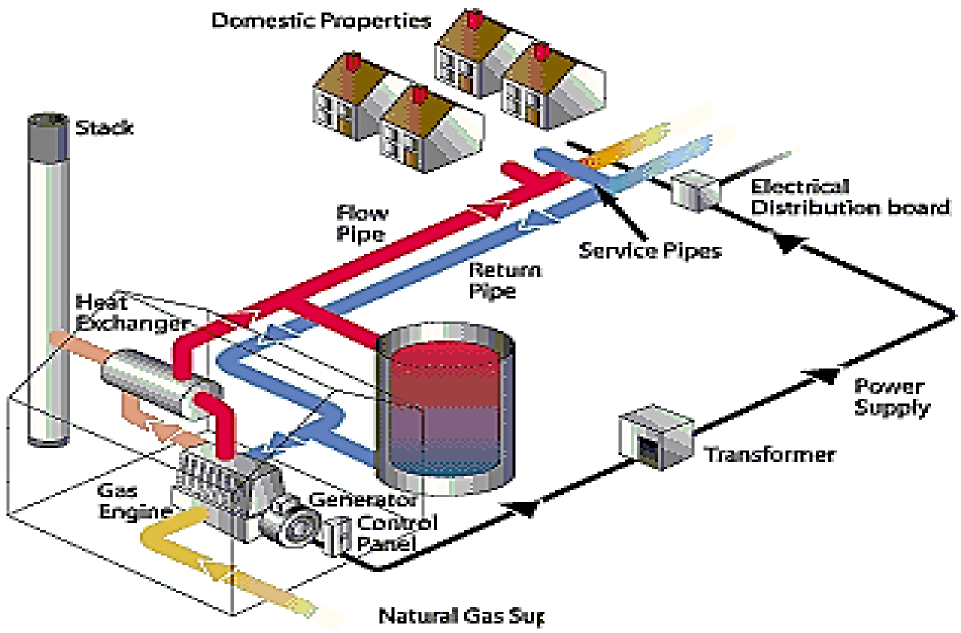

Figure 13: Typical DH system supplied by a natural gas powered CHP unit (adopted from: (PPSL, 2012))

The planning process of a DH system is a long-term undertaking. Complex territorial, institutional as well as social parameters need to be analyzed and dealt with. As presented above, DH is highly flexible in the utilization of resources, but also in the application of heat production units. For its rather high investment costs and a long payback time (see chapter 9), a technically possible and economically reasonable solution has to be found, complying with the determined sustainability criteria. The following factors have been determined as the ones being most influential for the planning process.

6.2 THE ANNUAL LOAD DURATION CURVE

First of all the actual demand, distributed over the year, including peak loads, needs to be determined. The annual load duration curve is based on monthly, annual or daily consumption data. As mentioned above, heat demand fluctuates between individual consumers, depending on housing type, insulation quality as well as consumer behavior.

The easiest way to obtain consumer data about their yearly heat demand is to ask them. With newly constructed houses, however it is not possible to refer to real consumption values.

Approximate annual values can be gained by literature and it can be assumed that the dependency of the space heat requirement and the outside temperature is almost linear (Dötsch, et al., 1998, p. 10).

As described in Chapter 5.2 and presented in Figure 14, there are very few hours with a high peak load, corresponding to the coldest days of the year. The base load consists of a very constant part, determined by the hot water consumption, and a rather low space heat demand on mild days. The area underneath the curve equals to the total annual heat consumption within a DH network.

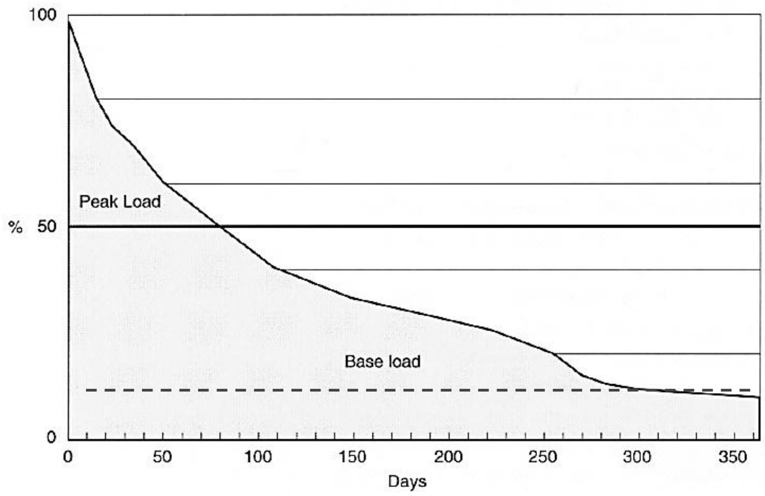

Figure 14: Duration curve of the annual heat demand, subdivided into peak and base load demand (adopted from: (Armitage, et al., 2002, p. 41))

6.3 THERMAL CAPACITY

In order to determine the demanded boiler (and/or CHP) capacity the total annual heat demand (MWh/a) is divided by T_b (h), which corresponds to the full load hours of a consumer. As done by the engineers of WärmePlus, these hours can be fixed to 1700 hours.

The nominal capacity, however cannot simply be determined by the sum of (existing) individual boiler capacities. This would lead to excessive investments, as past heating installations were often oversized. Additionally, an aggregation factor has to be considered, again lowering the overall demanded thermal capacity (AGFW, 2012 (b), p. 7). This factor meets the fact that not all consumers are extracting thermal energy of the grid simultaneously. The factor decreases by the number of consumers, which are connected to the grid. For the factor being based on practical experience, authors state different values going down to 0.62 (Zinko, et al., 2008, p. 33; AGFW, 2012 (b), p. 7) or even 0.5 (Obernberger, 1997, p. 6f), if a quantity of consumers of >23 is reached. The aggregation factor is not only influencing the capacity of the thermal unit but also the dimensions of the pipes, as different diameters can transport varying amounts of heat.

Table 4 displays a calculation example for a capacity determination of a fictional district which has about 2000 connected flats and an annual heat demand of 130 kWh/m²a. This district is modeled in the cost evaluation chapter 9.2 where the investigation area is presented in detail.

The resulting total annual heat demand of about 26,000 MWh, plus total thermal losses about 6170 MWh and the application of an aggregation factor of 0.65, result in a required thermal capacity of 11.9 MW.

Table 4: Theoretical building stock, with a set average heat demand, and a corresponding total demanded thermal capacity of the heat generating power unit

Heated area (1000 m²)	203	Average heat demand (kWh/m²a)	130	Full load hours	1700
Total heat demand (MWh/year)	26,450	Total energetic losses (MWh/a)	6170	Aggregation factor	0,65
				Capacity (MW)	**12.6**

The relation of the annual duration curve to the overall capacity is illustrated in Figure 15.

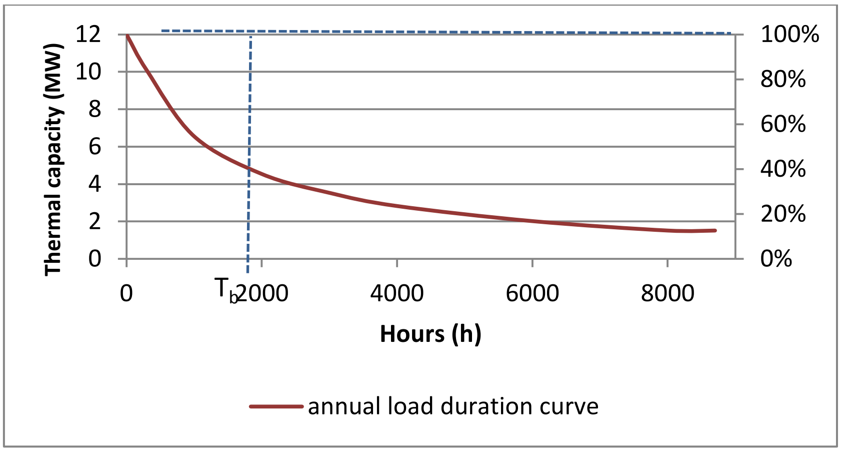

Figure 15: Thermal capacity in relation to total annual heat demand

6.4 HEAT GENERATION

While some power units are suitable for base load supply and others for base and/or peak load supply, it has to be decided whether one or two (or more) boilers or CHP units shall be applied in order to cover the total load (Dötsch, et al., 1998, p. 13).

According to Dötsch et al. (1998, p. 13) the capacity of the base load provider lies between 10 – 40% of the maximum power capacity, usually covering about 60 – 80% of the total annual heat demand.

In order to “secure the operation of the most efficient and most cost-effective plant” during base-load periods (IEA, n.D., p. 56), often run on RES and/or CHP units, a priority regime needs to be defined. Plants need to be combined so that they can operate on nominal load, i.e. highest efficiency, and only seldom on partial load (Hausladen & Hamacher, 2011, p. 65). More expensive stand-by or peaking plants (per generated kWh), such as heating only boilers, “will generally be the most flexible low-capital-cost boiler plant(s) obtainable” (Armitage, et al., 2002, p. 49), often powered by fuel oil or natural gas. The main characteristics of base load or peak load heat generators are presented in Table 5:

Table 5: Characteristics of base and peak load heat generators (based on: (Dötsch, et al., 1998, p. 15))

Base load heat generator	**Peak load heat generator**
Operation close to the design point (operation at highest efficiency)	Operation in partial load
High operation hours	Few operation hours
Few load changes	Frequent load changes
High capital costs	Low capital costs
	High disposability

CHP technology offers several technical, economic and environmental advantages compared to other technologies, generating heat and electricity separately. Conventional fossil fuelled power plants have had an average efficiency of 35% for many decades; until today levels could be increased to about 45%. With efficiency levels of up to 90%, Co-generation units can lower fuel consumption by 20-30% compared to conventional energy production systems. Less primary energy is needed in order to cover the same amount of end-use energy demand. CHP units can therefore be regarded as “low carbon energy solutions”, as fossil fuels emit less CO_2 emissions, per usable energy unit (kWh) (Andersen & Lund, 2007, p. 289; IEA, 2011, p. 6).

This gain in efficiency can be achieved, for heat and electricity being produced at one time, not discharging the produced heat of the electricity generation. Typically CHP units are combined with DH grids, often having one or two CHP units, boilers for peak load operation and thermal storage tanks, offering a more flexible operation (Andersen & Lund, 2007, p. 289). Figure 16 illustrates the primary energy consumption within a CHP plant compared to separate heat and electricity generation.

Nowadays also small CHP units are being utilized, distributing heat in smaller urban areas, offering environmental advantages like the possibility to use regional biomass resources and additionally the option to recycle the ashes locally without having high transport costs (Andersen & Lund, 2007, p. 288).

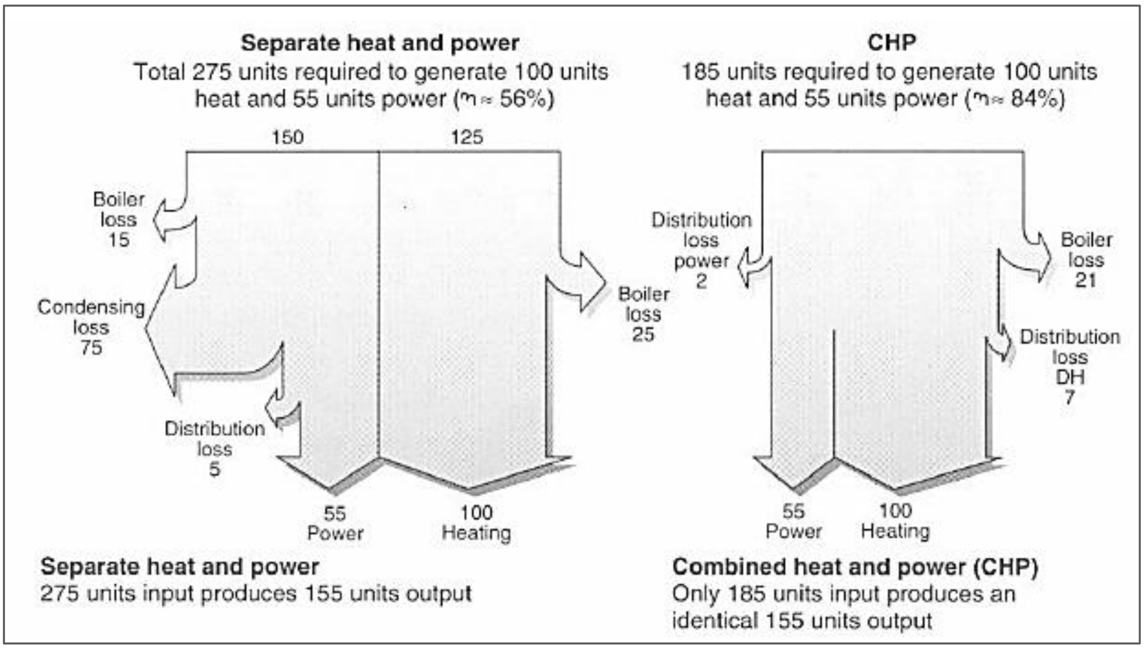

Figure 16: Primary energy consumption of CHP based or separate heat and electricity generation (adopted from: (Armitage, et al., 2002, p. 32)

In a request of the opposition parties in the German Bundestag, regarding an amendment of the CHP Act in 2011, the importance of the application of CHP units, within the aspired energy transition has been underlined by the following statements (Steinmeier, 2011, p. 2):

- CHP is the most efficient form of both, fossil and RES combustion. Therefore it is said to be a vital component of the energy efficiency strategy of the federal government.
- For being a mature, high efficiency technology, CHP can substantially contribute to lower GHG emissions.
- CHP (particularly powered by natural- or biogas), is highly flexible and is therefore a practical technology to be used in combination with increasing amounts of intermittent renewable capacity (see below).
- For being a decentralized plant, located close to the consumers, it can take some load of the high voltage grid, also increasing competition on the electricity market.
- Modern CHP units can rather easily be (re)designed for the combustion of RES like biogas.

With a quickly developing market of RES for electricity production, and due to its characteristic fluctuating electricity generation, backup technologies, which "must be capable of changing their level of electricity production at short notice" (IEA, 2011, p. 21) need to be installed in order to compensate for a highly volatile market. Gas fired power plants provide the possibility for a fast up or down regulation, however, as stated by the IEA (2011, p. 21), "it would be counter-productive if renewable energy technologies introduced in part to mitigate carbon dioxide emissions end up losing some of their green credentials because of required gas-fired backup systems". Co-generation technologies can support the stabilization of the electricity grid concerning frequency and voltage (Andersen & Lund, 2007, p. 289) simultaneously cutting carbon emissions (IEA, 2011, p. 21).

6.5 OTHER HEAT SOURCES

As described in Chapter 5.3 which delineates the current heat market and outlines some prospective developments, biomass today is the number one RES on the heat market. Solar thermal as well as geothermal energy will gain more importance in the future, though, most probably also on the DH sector. Therefore a brief introduction to these technologies and resources shall be presented here.

- Biomass is the only RES which is able to replace fossil fuels in an equivalent way, as it is a resource which can be stored before being converted into usable energy. It is defined as "stored solar energy" and is available in a diverse range of materials, "wood residues, organic wastes, crop residues, crops grown specifically for energy production, animal wastes, etc." and can combusted in solid or gaseous condition (IEA, 2007, p. 30). A drawback of this resource; however is that it is available in limited amounts, and that it stands in conflict with regard to utilization. Its utilization needs to guarantee sustainability, in terms of production, transport, quality, etc. (IEA, 2007, p. 30). Biomass can be combusted in both, a boiler or a CHP unit, covering hot water as well as space heat demand. Units can be operated fully automated, requiring low input of maintenance work, except of fuel delivery and ash collection.

- Solar thermal energy has been applied as mainly a hot water provider for several years. The system works in circulating a transfer fluid (often water) through pipes and is heated inside the solar collector panel, transporting the heated energy carrier to a heat exchanger. The heated water is stored in a storage tank. The absorption capacity depends on material and on location (IEA, 2007, p. 27). About 60-70% of the domestic hot water demand can be covered with small scale installations, which will have a size of typically 1-1.5 m^2/person (Heidemann, et al., 2005, p. 30). However solar thermal applications can also cover some share of the space heat demand. As this demand arises in the winter months, when insolation is considerably lower, seasonal fluctuations prevent an optimal match of heat demand with the technology, though (IEA, 2007, p. 28).

  When applying short term storage tanks, between 15 – 20% of total thermal energy demand can be covered (Heidemann, et al., 2005, p. 31).

  Solar thermal applications have a rather high capital cost, in comparison to conventional systems and its pay-back period will usually vary between five to ten years (IEA, 2007, p. 27). The ESTTP however, points out that market prices could be reduced by about 20%, for each 50% increase of installed capacity in the past (ESTTP, 2007, p. 29).

- Another potential source supplying heat for domestic usage is geothermal energy. It is said to be “an inexhaustible source of energy” (IEA, 2007, p. 32) and is independent from climatic influences. While there is a great difference in deep geothermal and shallow geothermal systems, in the case of WärmePlus only close to surface heat pumps are of importance. Deep geothermal technologies benefit from very high temperatures and are applied, in order to generate electricity. Shallow geothermal HPs are driven by electricity and generate heat in a certain ratio. This ratio between heat production and electricity consumption is called the coefficient of performance (CO) and often lies at about 3.5. Heat is usually supplied at comparably low temperatures and will only be applicable with under-floor heating systems e.g. (IEA, 2007, p. 32).

  A heat pump needs about one third of energy input of a gas boiler. As electricity is about three times the price, there are hardly any cost savings, with today’s price levels. When compared to an oil boiler or direct electricity heating, or considering prospective price increases, HPs could provide savings

6.6 THERMAL STORAGE

The importance of thermal storage has been mentioned before; still its importance shall be highlighted once more. As the annual heat load duration curve does not contain any information about the weekly or even daily fluctuations of the heat demand, which are dependent on factors like operating hours or consumer behavior, it only builds the basis for a decision on technical options as well as operation strategies like CHP work load as well as storage capacity and suffices only for a rough initial planning; however, for a more detailed planning of the real work load of a CHP unit or necessary thermal storage capacities e.g., a daily load profile should be created (Dötsch, et al., 1998, p. 12).

CHP units can often not be operated economically, if they have to cover part load (base load plus a certain share of the peak load – often having to switch between on and off modus). In order to avoid this (the same holds true for boilers) thermal storage tanks are applied, which can level out the demanded heat production, increasing the base load operation of the production unit. The storage capacity should at least cover 50% of the hourly heat demand (Dötsch, et al., 1998, p. 14).

A thermal storage can contribute to a peak shaving or in some cases even load leveling, as presented in Figure 17 and can therefore again lower the demanded thermal capacity or fuel use of the peak boiler or maximize electricity revenues of CHP systems. Additionally a storage tank offers the possibility to “meet short term rapid increase in demand” (Armitage, et al., 2002, p. 50).

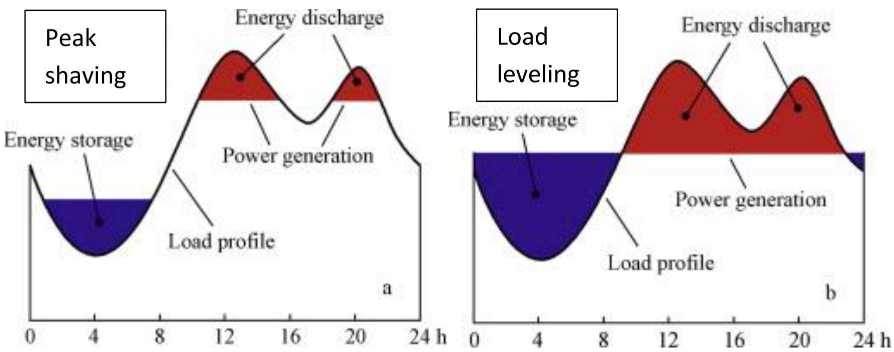

Figure 17: Illustration of storage capabilities (based on: (Chen, et al., 2009, p. 292))

As mentioned in chapter 5.1.2, CHP plant operators are able to trade electricity on the spot market or on the day-ahead market; with flexible gas fired plants on the regulating power market. In hours in which there is a lot of electricity production of RES (probably low paid hours), CHP plants will probably not generate power. DH girds will then be provided with thermal energy of the storage tanks, which are filled in hours, in which there is little electricity of RES and in which higher electricity prices allow a profitable operation (Andersen, 2007, p. 6&11). Beer (2011, pp. 8-10) calls this decoupling of electricity and heat generation (due to the thermal storage) a functional electricity storage capacity, as in some way CHP units can act as a storage system in offering some kind of reserve capacity. If the thermal storage capacity is too low, only a share of the total 'electricity storage capacity' will be available for grid balancing. The possible electricity sales offer additional profit opportunities for DH grid operators, especially interesting for otherwise cost-inefficient grids. RES integration, however, will only be achievable when both systems are able to communicate, and if there are incentives for CHP unit owners to run their units current regulated (Andersen & Lund, 2007, p. 288).

6.7 CUSTOMERS INTERFACE

There are basically two different connection principles, which transfer the delivered thermal energy of the DH network to the internal system of the consumer. The two systems (primary and secondary network) can be combined via a direct or an indirect connection. While the indirect system has a hydraulic separation between the DH network and the heating system, i.e. two circuits, the direct one is characterized by the fact that the same circulating energy carrier passes through the distribution network and the radiators. For hot water, in almost all cases a heat exchanger is used (Euroheat & Power, 2008, p. 32f).

As direct connection systems have the three main disadvantages of difficult pressure compatibility, contamination of the energy carrier which again leads to more likely disturbances of the grid, and leakages in individual houses effecting the whole grid, usually indirect systems are applied (in Germany). Indirect systems have the disadvantage, that return temperatures are generally higher; however modern heat exchangers are able to extract the largest share of the usable energy (Skagestad & Mildenstein, n.D., p. 53). According to Euroheat & Power (2008, p. 33) the temperature difference between the two systems should not be more than 3°C. In order to achieve this, the heat exchanger needs to be sized optimally. This also holds true for the heat exchanger having to be able to extract enough heat of the primary circuit at all times, also when outside temperatures result in lower supply temperatures (Euroheat & Power, 2008, p. 9). When installing an individual storage tank, the capacity of the heat exchanger can be lower than in a system without a tank. System costs will initially be somewhat higher; however total losses are lower (Olsen, et al., 2008, p. 8).

It is important to mention, that the DH customer has to follow the rules, which have been stipulated in the contract with the DH operator, in order to guarantee a “secure energy efficient operation” (Skagestad & Mildenstein, n.D., p. 69). Whether this is the case with the networks of WärmePlus will be discussed in the analysis section.

Besides the heat exchanger units the valves need to be dimensioned correctly, as they also largely affect grid performance, e.g. return temperatures and pumping costs (Euroheat & Power, 2008, p. 17).

7 INFLUENCING FACTORS ON GRID SUSTAINABILITY

For the heat markets being highly competitive, heating system providers face increasing cost pressures. This again leads to the need of minimal heat generation costs for DH system operators. Costs result from initial investment costs as well as from operation and maintenance costs, including fuels. In order to minimize these costs, authors (e.g. (Engelmann & Krimmling, 1998; Wolff & Jagnow, 2011; Zinko, et al., 2008)) agree that making the networks as efficient as possible, be it in heat production or heat distribution, is one major issue for DH operators. Technical solutions need to be developed, which result in minimized production costs and thermal losses.

After the most important technological components were introduced in the previous chapter, this chapter describes the most important operational variables (often dependent on the technological grid components) and highlights the importance of their optimized performance.

There are several factors important to be known about, either presenting important reference values for a holistic evaluation, or influencing heat losses in direct or indirect way. The following subchapters shall present an overview about these factors, which then shall be applied to existent networks in a later step.

Zinko (2005, p. 62) states, that “as long as the necessary load can be supplied and the customer’s request for comfort is met”, the optimization of district heating networks is often focused on the heat production, rather than additionally taking the distribution into account. However, high operational temperature differences can be seen as an essential part of an optimal system operation. The AGFW (2012 (b), p. 3) even states that there is no technical requirement, which is disregarded or even ignored, as is the low return temperature.

7.1 TEMPERATURE CHARACTERISTICS

The energy storage capacity of a DH grid depends on the temperature spread between the supply and the return temperature. Also the total heat energy extraction is dependent on the achieved temperature, but also on the mass flow, which is a second determining variable: the lower the return temperature, i.e. the larger the temperature difference to the supply temperature, the more energy is extracted by the consumer, in relation to the mass flow of the energy carrier. The following formula describes this relation:

$$\boldsymbol{Q = m * c * \Delta T}$$

with:

Q as the heat extraction in MWh

m as the mass flow in kg/s

c[1] as the specific heat capacity of energy carrier in kJ/kg K and

$\Delta T = T_{Supply} - T_{return}$ as the temperature spread between the supply and return flow in Kelvin (K).

[1] *Within the operation temperature frame, the heat capacity of water can be regarded as constant, although it is a fluctuating variable in theory* (AGFW, 2012 (b), p. 7)

Due to this relation the amplitude of the temperature spread (between the supply and the return temperature) is essential for the profitability of a heating grid (AGFW, 2012 (b), p. 7). Therefore it should be in the interest of the heat provider to allow the return flow to cool down at its maximum. This maximum value is equal to the usable heat content (exergy) which is the share of total energy within a system which can perform work when it is brought to thermal equilibrium within its surrounding. Besides this, there is also a not usable share in the total energy (anergy) which is not able to perform work. An optimal temperature reduction should be achieved, with a theoretical optimum at its surrounding temperature (Knierim, 2007, p. 57); however there will always be a share which is only theoretically usable, not offering economic incentives.

The technologically achievable (optimal) temperature spread is stipulated within the technical connection regulations which are individually drafted for each network during the planning phase; however they are also dependent on national codes and principles which vary from country to country (see Table 6).

Table 6: Reference values for demanded temperature levels in different nations (based on: (IEA, n.D., p. 53))

Country	Supply Temperature	Return Temperature	Hot Water
Denmark	70	40	<60
Finland	70	40	55
Russia	95	75	50
Poland	85	71	55
Germany	80	60	55

The table lists hot water, as this, besides comfort issues, also needs sufficiently high temperatures for health reasons. This is regulated by the European Directive 98/83/EC which ensures the safety of water for human consumption (Euroheat & Power, 2008, p. 8). In order to guarantee a certain temperature in each substation the supply temperature provided by the production plant should always be about 10°C higher (Euroheat & Power, 2008, p. 3).

The course of the supply temperature usually follows a determined temperature profile which relates to the outside temperatures. Also a usual temperature profile of the return temperature will not show a constant temperature level but will rather also follow heat demand, i.e. the outdoor temperature. While the supply temperature is reduced with lower heat demand (in order to reduce thermal losses), the return temperature is more likely to increase for technical reasons.

Figure 18illustrates the supply and return flow temperature profiles, as well as the medium temperature, which is used in order to determine the heat losses of a system (outlined in the next sub-chapter).

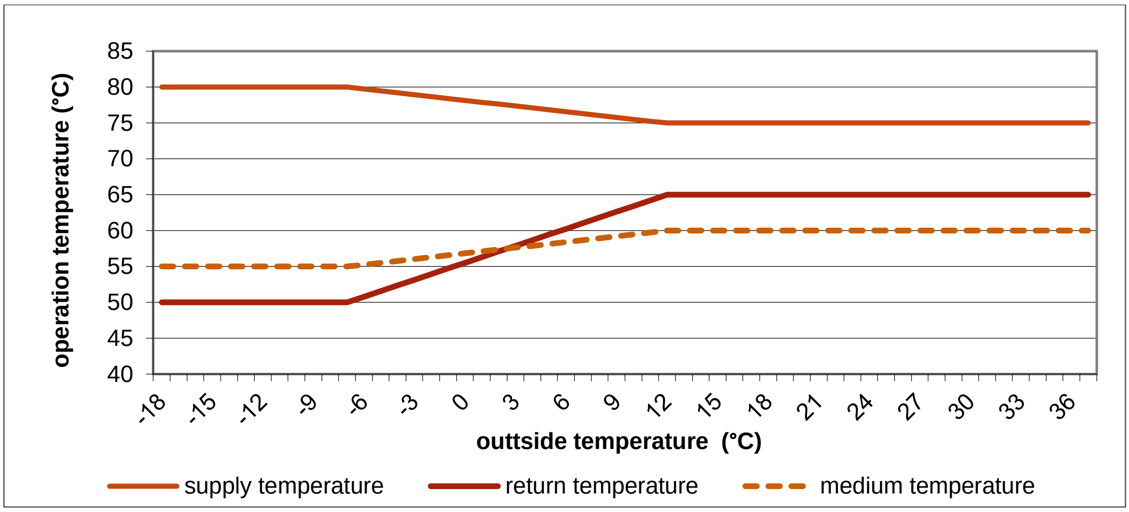

Figure 18: Temperature profile of a district heating network, including supply, return and medium temperatures, dependent on the outside temperatures

If the consumer does not cool down the heating medium to the required temperature level three main issues apply (e.g. (Knierim, 2007, p. 96)):

1. There are higher energetic losses (see chapter 7.2) within the grid as the losses depend on the one hand on the grid length but on the other hand also correlate to the temperature profile of a network.
2. The mass flow needs to be increased, with a lower Δt, i.e. lower heat energy withdrawal (see equation above), leading to a higher electricity consumption of the system pumps which can be an important cost factor[2].
3. With CHP, condensing boilers and heat pumps the temperature level of the return flow is explicitly important, as the installations are dependent on rather low temperatures in order to achieve optimal efficiency.

Concerning the latter issue, a return temperature below 40°C (for oil) or below 50°C (for gas) needs to be aimed for in order to be able to technically utilize the condensing technology, i.e. for being able to use the latent heat of the water vapor in a more efficient way (AGFW, 2012 (b), p. 10; Dötsch, et al., 1998, p. 65). This means that condensing technologies and HPs as well as DH have the same technical demands, concerning return flow temperatures.

Figure 19 illustrates the relation of the amount of condensing water and the efficiency curve of a gas powered boiler, depending on the return temperature.

[2] *A calculation example of the AGFW* (2012 (b), p. 8) *shows a case where the return temperature is missed by e.g. 20°C (60°C instead of 40°C). The pressure loss increases by 41% and the pumping by 70%. Due to a rise in friction pressure the demanded pumping energy grows to the power of three, in relation to the growing volume flow.*

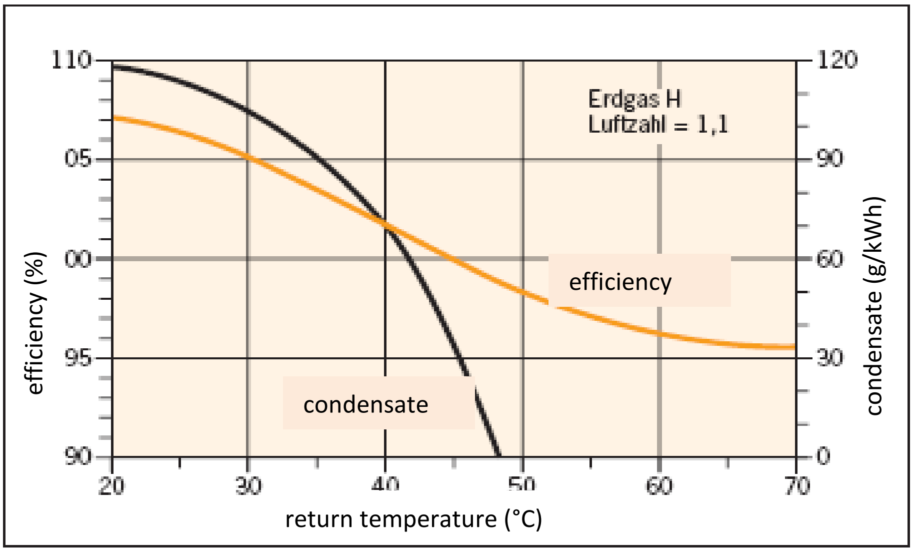

Figure 19: Relation between condensing temperature and efficiency (adopted from: (Hertle, et al., 2000, p. 3)

It is not enough only to potentially provide the heat via the network if the heating medium cannot be cooled down sufficiently within the customer's interface. A great issue for many DH companies is that the return flow can hardly be influenced by the grid operator but is rather dependent on the quality of the customer's installations as well as on the consumer's habits, often leading to temperature levels (high) above the ones stipulated between the grid operator and the consumer, or the ones listed in Table 6 (Knierim, 2007, p. 57; AGFW, 2012 (b), p. 8). A required temperature spread of at least be 30°C, as mentioned by Zinko et al. (2008, p. 63), is hardly met.

Zinko et al. (2008, p. 63) and Knierim (2007, p. 106) have determined three classes of malfunctions which can occur in a subsystem potentially leading to an elevated return temperature level:

1. design errors (missing hydraulic adjustment e.g.) or deficiencies in the radiator heating system,
2. design errors or defects within the hot water circuit,
3. defects in other components of the substations, like heat exchanger, heat meters etc.

These malfunctions might not only be problematic for the heat provider, but can also influence the domestic heat capacity, and can lead to problems in getting enough power or heating up the water and can consequently influence consumer's comfort and costs. This holds true for 1/3 of the cases. In 2/3 of the cases, however only the network operator is interested in lowering return flow temperatures (Zinko, et al., 2008, p. 63; Obernberger, 1997, p. 20) and it is difficult to put pressure on the customer to take effective measures.

There are options, like closing valves, in order to separate customers who don't comply with contractual terms; however this cannot be controlled by the system operators, as any technician can undo the intervention. Moreover drastic interventions like these probably do not contribute to a good customer relation.

With more effective metering records a two-fold pricing system could be installed, charging for total heat extraction on the one hand and for the volume flow on the other hand.

7.2 THERMAL LOSSES

Research on DH studies has revealed that, in contrast to the disregard of most system operators towards distribution optimization, there is a great interest in and a lot of studies on thermal distribution and transfer. That is hardly surprising, as profitability of DH networks very much depends on distribution efficiency. As mentioned in the introduction, thermal losses which are dependent on operational and outdoor temperature levels, pipe geometry, size and insulation materials, as well as the system structure, are therefore in focus of many researchers.

Bøhm and Kristjansson (2005, p. 1301), emphasize on the importance to reduce heat losses from the pipes, in order to "make district heating systems competitive", especially in low heat demand areas. In Scandinavian countries, they state, this was realized about 20 years ago when the competitiveness to other heat supply technologies became a more important issue, with decreasing demands.

Generally four major reasons for elevated energy losses can be found (e.g. (Zinko, et al., 2008, p. 42)):

1. Unfavorable load profiles, which could be smoothed out by storage capacities,
2. low connection ratio,
3. false grid dimensioning and bad pipe geometry or insulations,
4. unfavorable relation of supply and return flow temperatures.

Insulations have been improved by material and thickness and two or even more media pipes (twin pipes which aggregate two pipes in one casing e.g.) have been developed (see Figure 20). These aggregated pipes have lower thermal conductivity values as the total area exposed to the surrounding is smaller than for separate supply and return pipes (Zinko, et al., 2008, p. 65).

Figure 20: Illustration of one and two media pipes (gogeothermal.co.uk, n.D.)

Pipes are in constant contact with the soil therefore the thermal resistance between the heat carrier in the pipes and the surrounding constitutes of the two parts, thermal resistance of the insulation and of the soil. For changing soil-types, varying moisture content, as well as changing soil temperatures, the soil conductivity is difficult to determine (with dry sand and wet clay it varies between 0.5 W(mK) and 2.5 W/(mK)) and is therefore usually set to an average of 1.5 W/(m K) (Perpar, et al., 2012, p. 197)**.** In a proposed heat loss calculation method of isoplus (Isoplus, 2012 b, p. 18), a fixed soil temperature of 10° is used. As this variable plays a marginal role in thermal conductivity (k), this fact is regarded as being tolerable for calculations, even though soil temperatures differ throughout the year.

In older pipes (of the 1990s or before e.g.) aging of the foam is an issue. The study of Bøhm and Kristjansson (2005, p. 1304), which deals with "potential savings in heat losses and costs, states that already after few years, CO_2 blown foam (from these days), shows significant decline of insulation properties, contributing to an increase of the k-value. This ageing process however, could dramatically be decelerated within more recent developments of cycolopentane or polyurethane foam and later by the introduction of a diffusion barrier. Additionally insulations are thicker today than they used to be in the past (Bøhm & Kristjansson, 2005, p. 1302). In chapter 8.2 the decline of insulation properties is discussed on the basis of the loss interpretations.

Within varying insulation standards the pipe diameters also influence the total loss per m grid, for these having varying thermal conductivity values (k). Appendix B lists these different k values which determine the losses depending on the medium temperature according to the formula:

$$k = \frac{W}{m\,K}$$

and

$$K = \frac{(T_s + T_r)}{2} - T_{soil}$$

with:

K as the medium temperature, derived by

T_r as the supply temperature [K],

T_r as the return temperature [K] and

T_{soil} as the soil temperature [K].

Figure 21 illustrates differing values of heat transfer to the surrounding, depending on varying medium temperature levels, for single or twin pipes (of diameter DN 100) with different insulation standards.

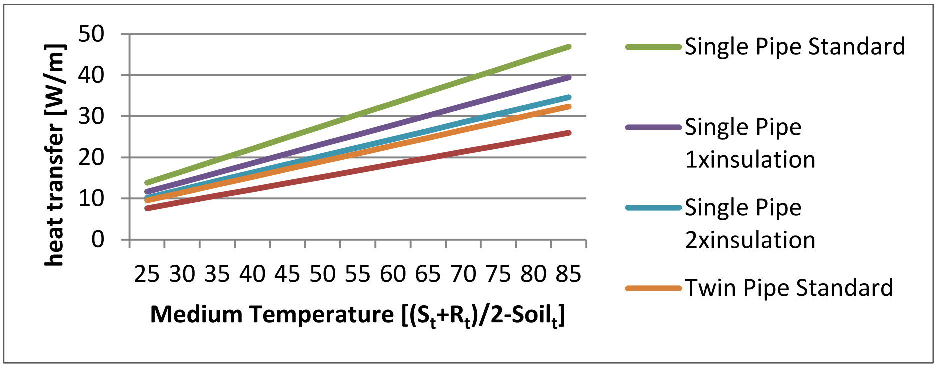

Figure 21: Heat transfer per m of the grid, depending on insulation standard at DN100 and varying temperature levels

Figure 22 shows different heat transfer values according to a standard single pipe without additional insulations, and a twin pipe with enhanced insulation, both in an often utilized diameter for supply pipes (DN 25) and a standard diameter for distribution pipes (DN 100) in smaller DH network. It gets obvious that heat transfer which is dependent on the medium temperature as well as the diameter of the pipes varies considerably.

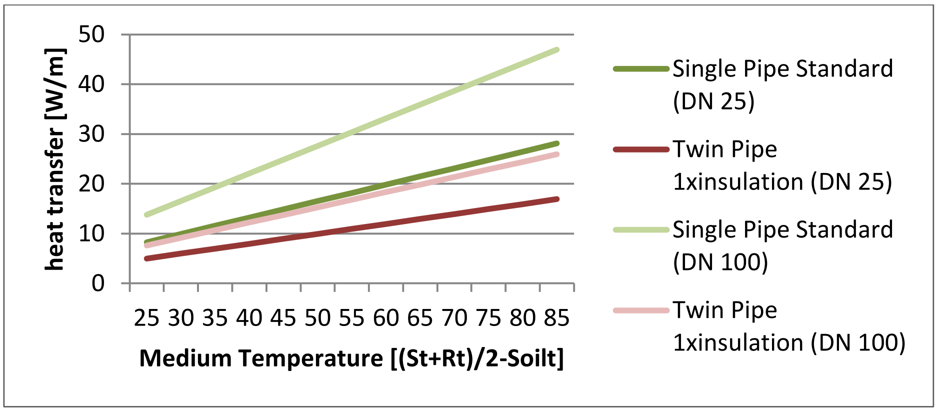

Figure 22: Comparison of heat losses for two pipe types in DN-25 and DN-100 for different medium temperature levels

The total loss of a DH grid is determined according to:

$$Q_{Loss} = \sum_{DN_1}^{DN_n} \frac{k * l_{grid} * t}{1000}$$

with:

Q_{Loss} as the total thermal loss [kWh]

k as the thermal conductivity of the pipes

l_{grid} as the total length of the grid for each pipe type and pipe diameter [m] and

t as the time [h] in 8760h per year

Wolf and Jagnow (2011, p. 25) refer to several studies listing losses between 250 and 600 kWh/(m a) or 5 – 50 kWh/(m² a). While their study presents an average total loss of heating grids of 11% (Wolff & Jagnow, 2011, p. 19) (referring to AGFW-Statistics) Engelmann and Krimmling (1998, p. 16) cite losses of 2 to 15%. The determined grid dependent losses for the grids of WärmePlus lie in this range for three of the four analyzed grids. One has higher values. Effective losses are higher for three of the grids, however. Results are presented in chapter 8.2.

Zinko (2008, p. 7) shows that the relative heat loss of a grid with a very low line heat density (see next chapter) can even lie at 80%, if certain measures are ignored. However, these can be regarded as extremes.

7.3 COST FACTORS

It is not the total loss, but the relative one compared to the demanded heat which is important for grid evaluations. There are three key values, which can be determined depending on available data:

1. The line power density (MW/km) which is the connected load referring to the total length of the grid.
2. The line heat density (kwh/(m a)) which is the total heat consumption referring to the total length of the grid.
3. The thermal density (kWh/km² a) which is the total heat transfer referring to the total network expansion.

While it has to be taken into consideration that there are several factors (see below) influencing operation costs, these values can demonstrate reference points, in order to allow comparison of grids within similar circumstances.

As the second key value is the one which could be determined on the basis of available data for the studied DH networks, it is the one being discussed here in more detail. According to Zinko et al. (2008, p. 5), it is also the most practicable one for determining the profitability of an investment. While the heat line density is proportionally high in rather compact building areas, it is generally rather low in areas with single family houses. In order to maximize the value, the connection rate should be close to 100% (Dötsch, et al., 1998, p. 3).

Concerning the fact, that there are several factors influencing grid performance, it is not surprising that studies differ a lot in their statements about minimum demand values for a cost efficient DH network. According to Bøhm and Kristjansson (2005, p. 1301f) low energy demand starts at line heat densities of around 2 GJ/(m a) which corresponds to about 550 kWh/(m a). Zinko et al. (2008, p. 9) refer to a study, which shows that even a line heat density of 350 kWh/(m a) can indicate profitability. Wolf and Jagnow (2011, p. 20), however, have determined a far greater threshold value of 4000 kWh/(m a) which, according to them, corresponds to the German average line heat density.

Wolf and Jagnow (2011, p. 20) stress on the fact that heat demand and therefore line heat densities will be lowered by factor three to four in the course of the coming years. The example of the line heat density of 350 kWh/(m a) which is based on Swedish circumstances, privileging

DH by charging high energy or CO_2 taxes on fuel oil, natural gas or electricity, shows, however that there are circumstances which allow profitability far below the values stated by Wolf and Jagnow (2011, p. 20).

The German government seems to have recognized this fact. While only grids showing heat line densities above 3000 kWh/(m a) were funded until 2008, heat line densities today can be as low as 500 kWh/(m a), in order to receive financial support (Wolff & Jagnow, 2011, p. 20).

As stated above, the different threshold values exist, as there are other influential factors, which affect total costs of DH, besides the level of the relative losses. “Total costs for district heating are the sum of the annual investment costs for heat generation, distribution network, customer installations as well as the energy costs, including heat losses and costs for pumping and maintenance“ (Zinko, et al., 2008, p. 5). With the construction of a DH grid being responsible for up to 50% of the total costs (Obernberger, 1997, p. 20), Denmark e.g. has been able to ensure economic viability by lowering their piping costs e.g. (Zinko, et al., 2008, p. 10). While heat conductivity could be improved, also relative pipe production costs could be lowered. Twin pipes e.g., having lower heat conductivity values, go along with lower installation efforts, hence costs. Even though the pipes are more costly, the total installation costs can be lower (Zinko, et al., 2008, p. 65). If constructions can be coordinated with other infrastructure investments (streets, wastewater e.g.) investments costs can be reduced even more.

Additionally pumping costs (which are also dependent on low return flow temperatures, and optimal volume flow) can be lowered severely by the correct sizing of the pipes as well as the pumps (for higher efficiencies with optimal capacity). If it gets too tight, however, more pump energy needs to be applied to overcome friction and to allow the passage of the necessary heat load (AGFW, 2012 (b), p. 7; Armitage, et al., 2002, p. 52).

Figure 23 illustrates the relation of all cost factors and shows the point of minimal total costs. The optimal dimensions for the grid are determined out of the optimal relation of the variables: capital expenditure (depending on the nominal diameter of the pipes) and the operating expenses (depending on the pumping costs, thermal losses and fuel prices).

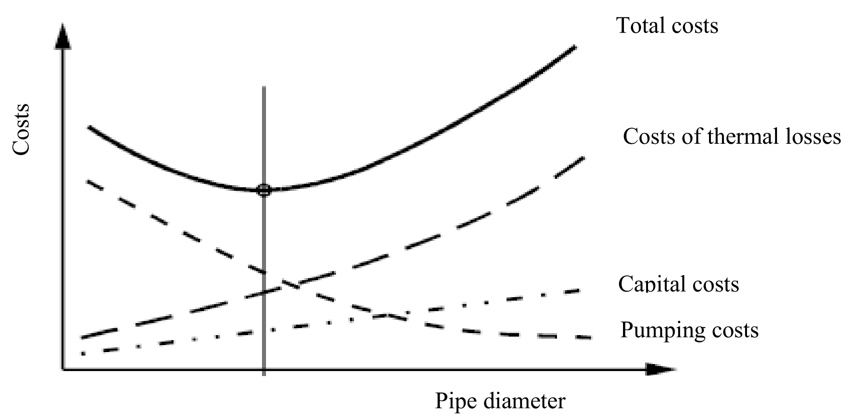

Figure 23: Cost optimization principle for DH networks (based on: (Obernberger, 1997, p. 9))

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7.4 ENVIRONMENTAL CONSIDERATIONS

As mentioned in the political section of this report political focus is set on demands side management measures, efficiency improvements as well as the expansion of RES. All of these targets have their individual costs and cost efficiency needs to be determined for each individual measure.

With climate change today being of major importance in environmental policy, most measures are likely to lower GHG emissions, although not all substitution activities will have an overall environmental benefit, when a life cycle assessment is carried out, as resources might be overused, or toxic materials need to be applied.

While the overall grid efficiency influences the cost effectiveness of a DH network operation it is also influencing the environmental performance. Environmental benefits, concerning emission levels, are obvious if highly efficient technologies are applied or if local RES are used as fuels, as long as they are consumed within their limits, i.e. in quantities which do not exceed natural replenishment, fulfilling a major sustainability criteria. Renewable energy sources (RES) with differing characters like being unlimited and flexibly applicable like biomass and unlimited but intermittent (like solar power and wind) can be regarded as "key elements in future cleaner" energy systems (Andersen & Lund, 2007, p. 288). Considering the current primary energy consumption of Germany, however estimations about the share biomass e.g. could cover vary between 5 - 15% (Wolff & Jagnow, 2011, p. 25).

Both, overall resource consumption as well as emission levels are influenced by higher grid efficiencies due to lower thermal losses e.g. Dalla Rosa et al. state that losses have the greatest environmental protection potential in the operation of a DH when regarding the overall life cycle of the grid (Dalla Rosa, et al., 2011, p. 2411), besides the decision on the fuel.

There are different methodologies how emissions of CHP plants can be determined. On the one hand there is the power crediting method where in a first step all emissions are related to the heat generation (leading to higher emissions per produced kWh heat compared to a boiler) and then subtracting the value, which is saved by replacement of electricity of the grid by the co-generated power. This method can even lead to negative emission values, however, when renewable electricity is replaced, there are no such savings (UBA, 2008, pp. 5 - 7). The second and currently applied emission determination method of the EU for CHP units is allocation method, where the individual efficiency values for the heat and electricity generation are allocated to the total fuel consumption. (UBA, 2008, p. 8). While the specific emission factors are listed in chapter 0 where they are applied in the evaluation calculations, an assessment of Conolly et al (2012, p. 49) for the future European heating development and the respective effects on emissions with DH shares of 30% and 50% (and current levels) with increasing shares of CHP, is presented with Figure 24. With a drop of the total fuel input for heat supply of about 40%, emissions would fall by 55%.

Another environmental advantage which shall briefly be mentioned results from better flue gas cleansing due to more efficient emission control filters, than applied with individual heating units.

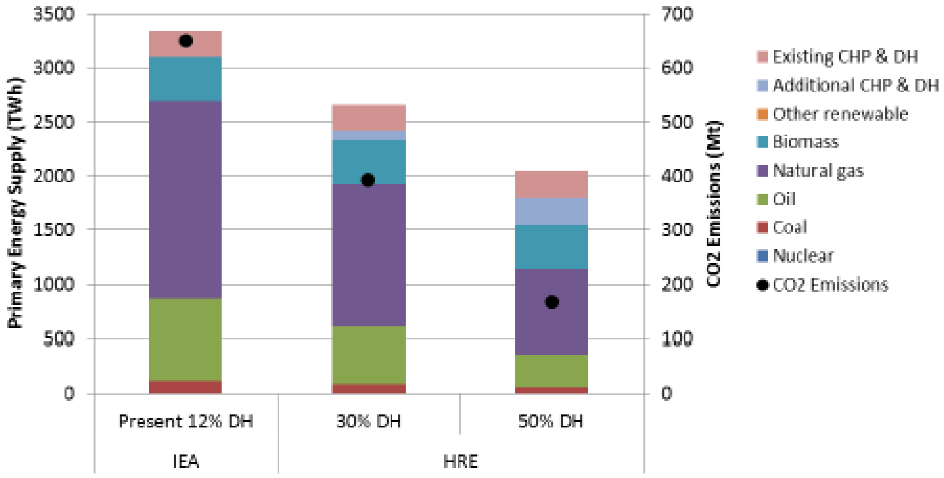

Figure 24: Primary energy supply as well as related GHG emissions for total heat demand of DH customers in IEA countries in 2010 and with a theoretical expansion of DH to 30% and 50% (adopted from: (Connolly, et al., 2012, p. 49)).

7.5 SOCIETAL ASPECTS AND *CONSUMER'S PERSPECTIVE*

The future of DH not only depends on technological opportunities and political regulations but also on consumer's attitudes, worries and desires.

The scope and the focus of the study has not allowed detailed interviews with thoroughly selected focus groups; however the social component is regarded as being very important within the topic at hand. Therefore literature studies have been undertaken. Consumer's opinions on DH will be presented in this chapter while the discussion chapter 10.1 focuses on the difficulties' of overcoming characteristic habits.
Chapter 6.1 lists various advantages of DH, some of them potentially having direct influence on consumer's decision on the 'optimal' heating system, like:

- Reliable heat supply
- Stable low prices
- Easily manageable for consumers as maintenance is in the hands of the operator
- Positive effect on health due to proper filters
- Value added due to job creation potential and possible utilization of local resources
- Lower fuel import dependency
- Better air quality, due to more effective filters

Upham and Jones (2012) conducted a study on the public opinion on DH. It is stated that most of the interviewees, who have switched their energy providers during the last years, did so because of lower cost and better reliability, whereas environment was consistently a low priority factor (Upham & Jones, 2012, p. 22). While these experiences refer to the UK, Zinko et al. (2008, p. 85) confirm that changing people's consumption patterns generally needs to offer clear personal advantages which may not be sufficiently obvious in the case of DH grids.

A study published by the Environmental Ministry of Baden-Württemberg (UM Ba-Wü, 2011) which deals with the general experiences of people with the Renewable Heating Act of the federal state, also confirms this impression. Surveys of different regional energy agencies have been analyzed and reveal that people tend to have (at least) a rather neutral perception of the issue of climate change, in regards to their compulsory climate protection measures demanded by the law. Just one out of 22 energy agencies reported a positive response (UM Ba-Wü, 2011, p. 10). The authors are rather surprised, as this result does not reflect the general impression one could have when talking to the population; other issues connected to the energy transition, however, like the erection of wind turbines, the planning of a pumped storage hydro power station, the construction of new high-voltage power lines, etc. equally depict great skepticism towards these measures. When people fear effects on their comfort or in monetary terms, the generally open attitude towards climate change mitigation measures abates (Upham & Jones, 2012, p. 22).

The study of Upham and Jones also describes one widespread concern of potential customers which is linked to a possible dependency (‘lock-in situation’) on one company as well as on one resource (Upham & Jones, 2012, p. 24).

Also a handbook on DH, published by the Ministry of Economics of Baden-Württemberg describes that rather than having doubts on the technological feasibility it is the fear of a financial risk and skepticism about the security of future supply (MWi Ba-Wü, 2007, p. 39). Even consumers who are in favor of this technology see a long term heating contract very critical. However, due to the rather high upfront costs and a rather long payback period the technology creates inevitably some kind of dependency, for both, the subscribers, as well as for the network operators. While consumers, who see heat supply as an essential service, depend on a reliable heat supply, the grid operator relies on a constant or growing number of consumers (MWi Ba-Wü, 2007, p. 39).

While the utilization of fossil fuels leads to an impaired balance of payments, one great societal advantage of applying DH, possibly powered by regional RES, could be the contribution for a local value added, possibly including a job creation potential. As mentioned before, the ‘threat’ of creating a monopoly, however often discourages many municipalities to determine the possible connection obligation (UBA, 2011 a).

Having a closer look at Scandinavian countries where DH shares are much higher than in any other mid European country, it gets clear that another prerequisite for trusting in DH technology is that local governments have wide ranging competence and are in intense dialogue with the population (Hug, 2012; Upham & Jones, 2012, p. 21).

As early as 1979, Denmark passed its first heat supply law and the county councils prepared definitive regional heat plans which aimed at showing:

- in which areas the various forms of heat supply should be prioritized, and
- where future heat supply installations and pipelines should be located.

Also around this time, taxes were applied to fuels used in heat generation with the objective of encouraging the use of environmentally friendly energy and efficient energy utilization. Biomass and biogas were exempted from taxes and thus politically supported long before other countries initiated their first attempts (ENS, 2005, p. 16).

Like it is the case in Germany, the first law on heat supply also gave local authorities the power to oblige new and existing buildings to connect to public supply (ENS, 2005, p. 15) The obligation to connect may be applied to both, new and existing buildings. For existing buildings, however, the obligation first takes effect 9 years after the owner of the property has been so informed (ENS, 2005, p. 25). The obligation to connect is not synonymous with obligatory purchase (ENS, 2005, p. 27). Due to the fact that a supplier may not charge any more or any less for heat than it costs to produce it prevents the fear people in Germany tend to have, that prices will increase unregulated (p.13). The early and clear political commitment to become energy self-sufficient combined with these clear regulations lead to high acceptance within the population.

8 PERFORMANCE ANALYSIS OF EXISTING DH GRIDS

After having introduced the most important components of a DH network, as well as described the most important determining factors for a profitable grid operation on a theoretical basis, these factors shall be analyzed on the basis of some existing grids, operated by WärmePlus.

The chapter shall provide information about specific grid characteristics, the status quo of their operation and efficiencies, as well as investigate on effects of varying operation temperatures. The obtained results will establish the basis for a discussion of the importance and the potential of certain optimization measures for each individual DH network. The clarifications of the previous chapters will form the basis for this analysis.

Having discussed crucial parameter for a profitable grid operation in chapter 7, and having shown their potential influence on existing grids of WärmePlus, these factors are completed with an outlook for future grid operation.

These prospective measures are applied within a second analysis, where the cost effectiveness of the investment for a future DH grid, is evaluated. Investments in a heating network or individual heating units are compared on the basis of a fictional district. A total of 48 combinations of the determined variables are compared, highlighting the importance of a profound knowledge of each single determined influential factor and the chances of technological innovations.

The following list presents factors which are evaluated within the initial grid performance analysis:

- What is the current overall efficiency of existing DH grids of WärmePlus and do values deviate from technological nominal values?
- How much energy could be saved by an achievement of lower return flow temperatures?
- How much energy could be saved by selective pipe replacement?
- What would be the cost savings for these measures?

In order to derive answers to these questions flow temperatures, pipe specific heat losses, mass flow, and pumping power need to be analyzed.

Table 7summarizes the applied fuel specific values for the calculations. Several sources needed to be consulted as no single source included all the utilized fuel types of the evaluated grids. Therefore it needs to be stated, that some values might not be entirely comparable.

Table 7: Fuel specific values which were applied for the calculations

Fuel	Unit	Calorific values (kWh/unit)	Prices for bulk purchasers (€/kWh)	Prices for individual consumers (€/kWh)	Emission factors (kg CO_2/kWh) (boiler)	Emission factors (kg CO_2/kWh) (CHP_{th})	Emission factors (kg CO_2/kWh) (CHP_{el})
Natural gas	m³	10.8	0.037	0.065	0.251	0.196	0.42
Bio gas	m³	10.5	0.09	-	-	0.073	0.157
Landfill gas	m³	7.6	0.06	-	-	-	-
Heating oil	l	12	0.055	0.068	0.319	-	-
Wood pellets	kg	4.9	0.035	0.047	0.029	0.056	0.12
Wood chips	kg	4.0	0.028	0.040	0.022	0.056	0.12
District heat	kWh	1	-	0.069	-	-	-

* calorific values were obtained from: (IINAS, 2012)
** prices were obtained from: (Federal Statistical Office, 2012; Schaubach & Witt, 2012; Wolff & Jagnow, 2011)
*** emission factors were obtained from: (KEA, 2011; IINAS, 2012; UBA, 2008), if available, and for CHP units if plants are existing – the described allocation method underlies the CHP units (see chapter 7.4)

8.1 DATA BASIS AND PROCESSING

Before the calculations are presented, a short overview about the obtained data is given. These data were provided by various departments of the company WärmePlus or the parent company badenova.

The data mining process has revealed that several operation data are only existent for short periods, or for reasons like renovation measures, missing or nonworking metering devices not available at all. Also time has constrained the process of data acquisition. The time issue got reinforced by the development of the calculation tool. The described Excel tool (see the methodology chapter 2.2.4), which was developed for the purpose of the study, but also for future investigations by WärmePlus, was designed flexibly, being able to compensate for certain data gaps, still being able to process data if they are available in the future.

Important input data for the grid evaluation are outside temperatures, the total resource input, the sales, temperature levels of the supply- and return flow and information about the grid components, heating units and applied fuels.

8.1.1 DATA ON ENERGY DEMAND

In regards to consumption values, data should ideally be provided in time series based on measurement data. While daily values would be preferable in order to be able to investigate the real grid performance, these values often had to be derived based on scientific assumptions. As the company charges their customers once a year, the sales values were only available as total annual heat demand values, for example. Together with rough information on the monthly fuel input, the monthly heat demand for the total network could be derived.

The average value of the demands of the months with medium temperatures above the heating limit temperature (15°C) was taken as a base load for hot water demand. The remaining heat load was then distributed over the months and in a second step, spread out over each day, depending on the outside temperatures. The load line follows the temperature profile, described with (Figure 18 in Chapter 7.1). The unevenly distributed hot water demand profile results from the fact, that months without temperatures below the heating limit temperature, thus without space heat demand, show rather high consumption values. Hot water demand in May e.g. has a peak as the month shows no days for which space heat was demanded. The fact that hot water demand seems to generally cover a very large share of the total heat demand in all analyzed networks, seems to deviate from reality when regarding space heat and hot water demand ratios, presented by various sources (shown in chapter 5.2).

Figure 25 and Figure 26 illustrate the heat demand distribution over the year dependent on the ambient temperatures, on the basis of the DH network of Stetten. Based on the provided data, hot water demand and space heat demand each account for 50% of the total heat demand.

Hourly fluctuations in heat demand, caused by consumption patterns during the night and day for example were not regarded to be of importance for the determination of the overall grid efficiency. When discussing the optimization of CHP operation e.g. hourly values would be needed. This however, as stated in the limitations, goes beyond the scope of the study.

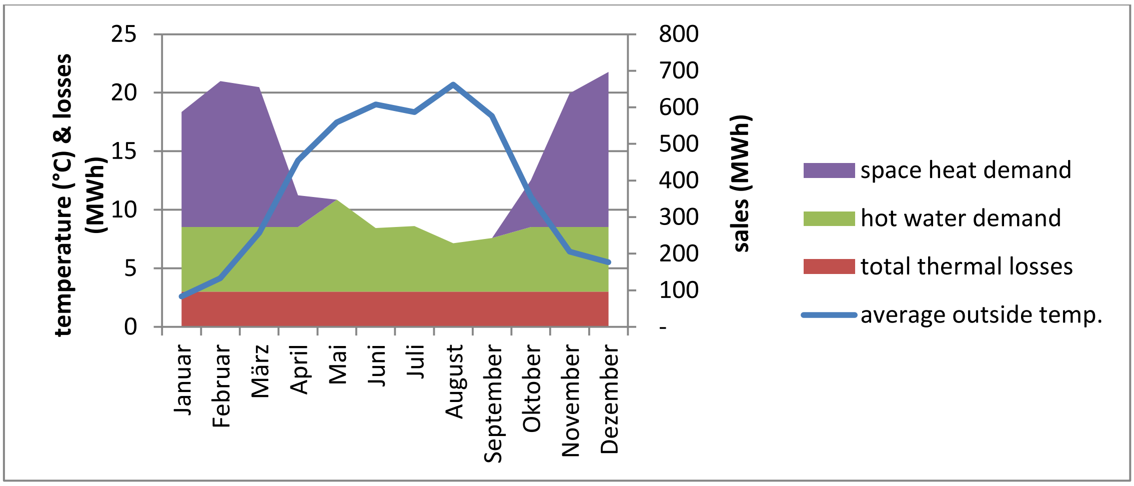

Figure 25: Heat demand load profile, dependent on outside temperatures.

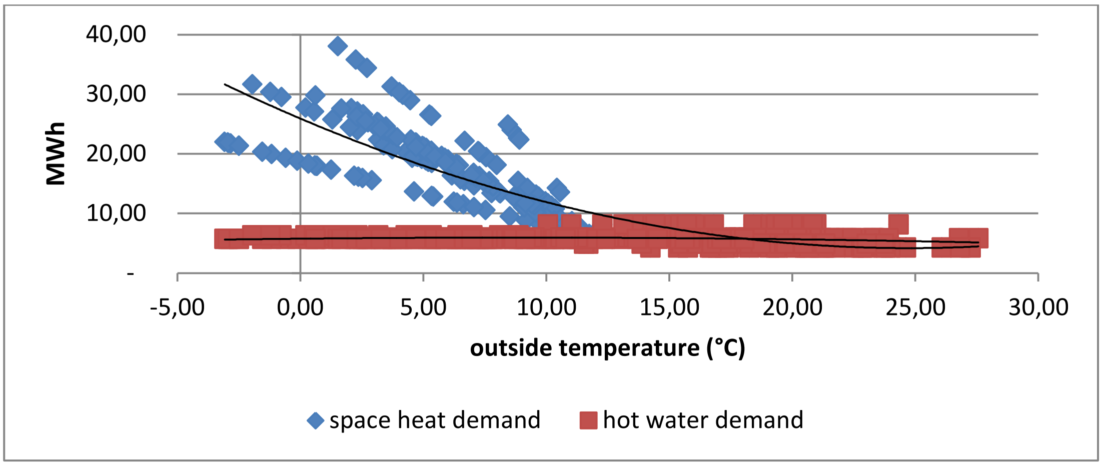

Figure 26: Heat demand distribution depending on the outside temperature each day of the year

8.1.2 DATA ON HEAT GENERATING UNITS

As described in chapter 6.4 the installation of specific heating units depends on customer's preferences as well as the load profile. In the case of the analyzed grids, both CHP units for the base load and boilers for the peak demand are applied. The information on efficiencies of the heating units and on the applied fuels was used for the demanded fuel input within a simulation of demand reductions due to building insulation measures (see chapter 8.4) as well as for the determination of emissions. An efficiency of 80% for the boilers and 90% for CHP units was used for calculations. Varying efficiency levels obviously changes the calculation results; therefore the parameter is addressed in the discussion of the outcomes once again.

8.1.3 DATA ON THE GRID

Information on the grid was provided by the company RegioData which like WärmePlus is a subsidiary company of badenova. It is responsible for the digital processing of spatial data in regards to energy networks, e.g. Data were available as shape files and were processed with the software package ArcGIS. They included information on grid type, age, length, material and diameter, for each single section. The grid type, insulation standard and the diameter were chosen as input parameter for further processing in the Excel tool. The age of the grid might be an explanation for thermal losses which are above the determined nominal values.

The shape files also provide information on the number of connected houses, as well as on the horizontal plane of the network. Together with maps from the internet (loerrach.de, 2012; stadtplan.freiburg.de, 2012) which were linked with ArcGIS, the networks can be better understood (see Figure 27). The supplied living space could not be provided but was estimated for two of the grids on the basis of the ground plan and the counted number of floors.

The colors of the pipes show their size distribution (from small - green – to larger - red) and the dots on the building contours illustrate a building age classification of < 1979 (orange), 1979 – 1992 (yellow), 1993 – 2002 (light green) and > 2002 (darker green). As the buildings were constructed in times with different insulation standards, these classes represent varying heat demand values and thus are important information for the performance of the DH grid. The networks are all based on an indirect heat transfer at substations within the buildings. The buildings in Vauban and ZO are colored blue. For these two networks, living space has been determined for statistical evaluations.

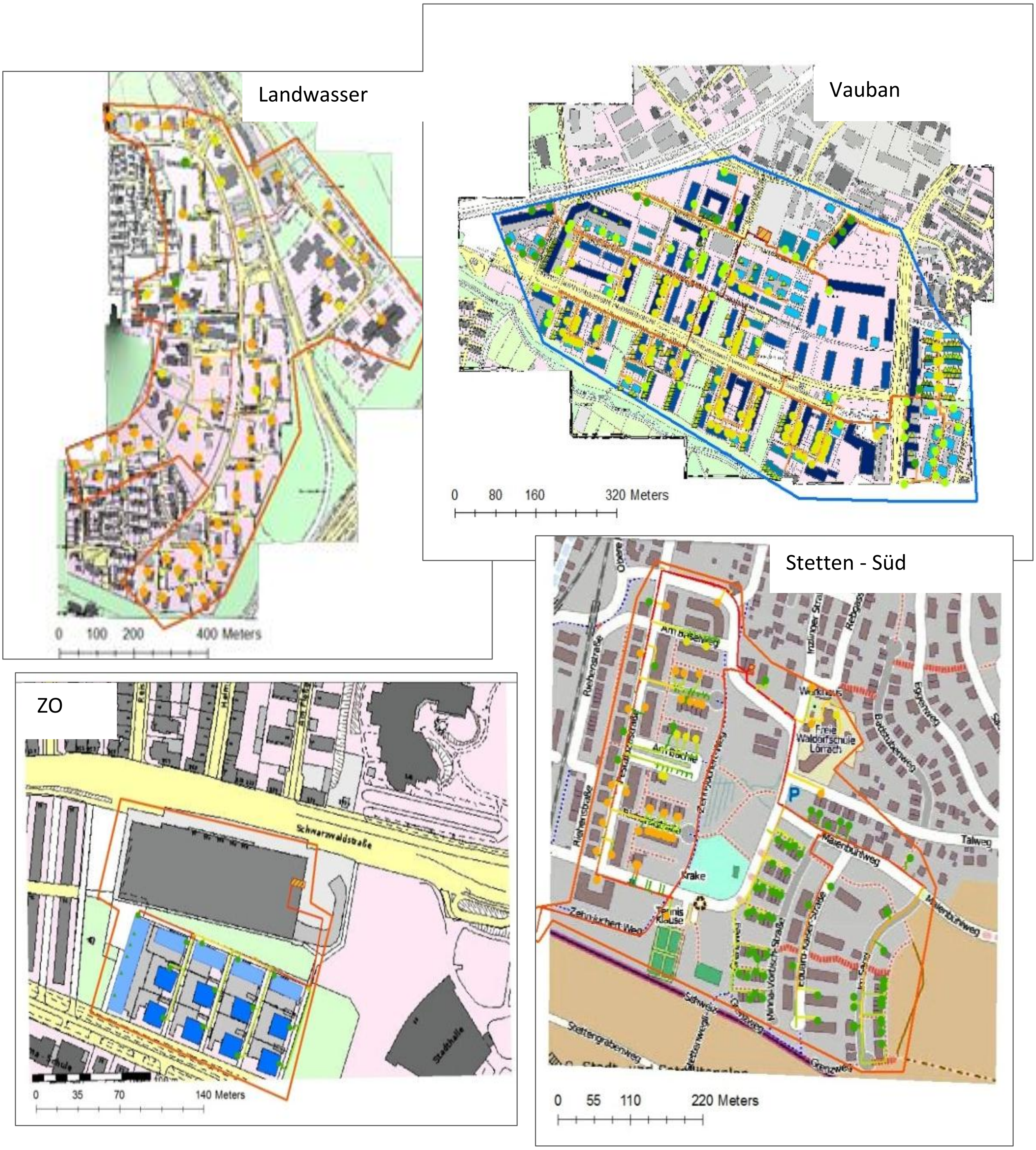

Figure 27: Overview of the four analyzed DH networks, Landwasser, Vauban, Stetten and ZO

8.1.4 DATA ON OPERATION TEMPERATURES

The Excel tool is designed for being able to process data on operation temperatures, for the days they are available. As no temperature data were available for none of the grids, for which the sales values could be obtained, the supply and return flow temperatures were determined according to Figure 18 (chapter 7.1), depending on the ambient temperatures and the resulting heat demand. The design temperatures for the two threshold temperatures for maximum and minimum load (depending on defined outside temperatures) were taken from the technical connection regulations which are individually designed for each grid.

Even though time series are not available for the operation temperatures, it was possible to get an insight in instantaneous operation values. The impression that temperatures are often divergent to the scheduled values was confirmed through discussions with several employees of WärmePlus. Therefore some kind of sensitivity analysis is carried out, deploying varying return temperatures. Knowing about the overall grid efficiency $\eta_{a,distr.}$ (difference between energy input and sales), and the theoretical thermal losses, based on information on the grid, assumption on the most probable return temperature can be made.

8.2 GRID CHARACTERISTICS

The DH network of Landwasser (city of Freiburg) is the oldest and the largest grid, of the four networks, evaluated in this study. It was constructed in the 1960 and extended in 1979 and again recently in 2011. Most of the houses were built around the time of grid construction and represent poor insulation standards, compared to today's required standards.

It is powered by two CHP units and has three peak or emergency boilers, powered by natural gas, bio gas (produced in a nearby biowaste gasification plant) and landfill gas (from the nearby landfill). The grid covers an area of more than half a square kilometer and has 64 connected buildings of varying sizes and with varying numbers of customers (flats).

With a total input of a of 49 GWh, and sales of 28.5 GWh heat and 6.6 GWh electricity it has a total line heat density of 3.74 MWh/(m a) and a network efficiency of 71%. Subtracting the determined thermal losses and the efficiency losses within the plants, 14% of the energy is missing. These values apply for the case that the stipulated return temperatures are reached.

Table 8 lists the most important network defining parameters the four chosen grids.

Table 8: Defining parameters for the four chosen DH networks

	Landwasser	Stetten Süd	Vauban	ZO
Year/ Period of construction	1966 & (1979 – 2011)	1995 – (2012)	1997 – (2011)	2004 – 2005
Boiler capacity (MW)	1 x 2.9 2 x 7	2 x 0.90	1 x 2.8 2 x 2.5	1 x 0.72 1 x 0.58
CHP capacity (MW)	2 x 0.85 th & 0.8 el	0.37 th & 0.24 el	1.3 th & 0.8 el	0.23 th & 0.14 el
Fuel type	NG, BG, LfG	NG, HO	NG, HO, WCh	NG
Provided area (km²)	0.54	0.23	0.37	0.03
Connected & coupled houses	64	112	169 & 145	12 & 4
Living space (km²)	ns	ns	0.17	0.014
Grid length (km)	7.63	6.0	6.71	0.60
Grid type (DN and insulation)	DN 25 – 400 Single Pipes Standard – 2x insulated	DN 20 – 125 Single Pipes Standard – 2x insulated	DN 25 – 250 Single Pipes Standard – 2x insulated	DN 25 – 100 Single Pipes Standard
Temperature levels (St/Rt in winter & summer)	100/30 & 70/40	85/30 & 70/45	90/30 & 70/40	80/30 & 75/45
Input (MWh/a) per ressource	29,160 (NG) 17,829 (BG) 2,037 (LfG)	6,027 (NG) 31 (HO)	16,497 (NG) 205 (HO) 1,847 (WCh)	3,239 (NG)
Sales (MWh/a)	28,520 (th) 6,626 (el)	4,220 (th) 984 (el)	11,432 (th) 3,552 (el)	1,434 (th) 745 (el)
Line heat density (MWh/m a)	3.74	0.70	1.70	2.40
Heat density (MWh/km² a)	52,815	18,107	30,898	47,812
Heat demand (kWh/m² a)	ns	ns	69	105
Losses (MWh/m a)	0.23	0.16	0.18	0.18
Losses via grid – based on TAB-temperatures	5.9 %	18.2 %	9.5 %	7.1%
Missing energy	14 %	- 1.3 %	4.1 %	21.6 %

The DH network in Stetten (city of Lörrach) has two parts. The western part was set up in 1995 and is connected to houses, which were constructed about two to three decades before. The eastern part supplies houses, which were built around 2003 – 2005; also the corresponding part of the grid originates from this period. This network is supplied by two boilers and one CHP unit powered by natural gas (99%) and a tiny share of heating oil. Within an area of 0.23 km² a total of 112 houses are supplied. Even though the area is less than half of the area of Landwasser, the connections are twice as much. For the many single connections the total grid length is six kilometers – only 1.6 km less than in Landwasser. This leads to a low line heat density of 0.7 MWh/m a, and thermal losses of 18.2% within the grid.

While the network of Landwasser exceed the theoretical losses by about 14% and therefore needs measures which support a more efficient operation, Stetten seems to succeed in lowering the return temperature to the demanded levels. As the sum of determined efficiency losses, grid losses and total sales even succeed the real fuel input by 1.3%, the temperatures might even be lowered below the stipulated temperature level.

The shares of energy sales and losses and the discrepancy to the total fuel input are illustrated in

Figure 28. While with Stetten (left) there is no such discrepancy the network ZO (right) which is described below, shows a great gap.

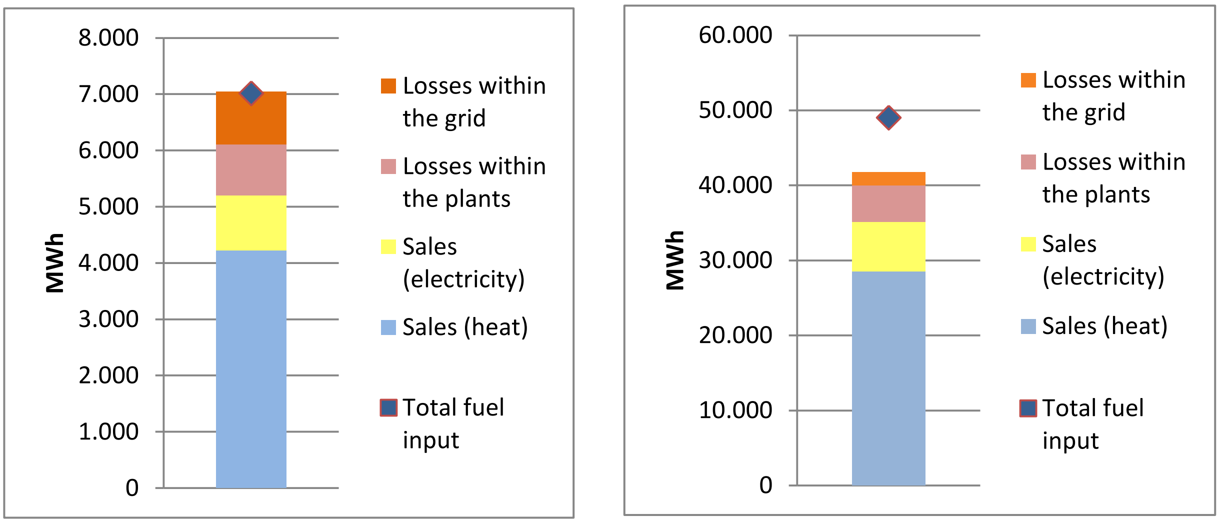

Figure 28: Comparison between the effective fuel input and theoretical demands for sales and thermal losses for the DH networks Stetten (left) and ZO (right)

As the medium temperature of the grid is relatively constant throughout the year, also the correlating total losses are relatively constant (Figure 25); the relative losses however vary depending on the season, i.e. the ambient temperatures (see Figure 29). In the case of Stetten (again assumed that the targeted return temperatures are reached), relative losses fluctuate between 8 and 42% in cold winter days and at temperatures exceeding the heating limit temperature, respectively.

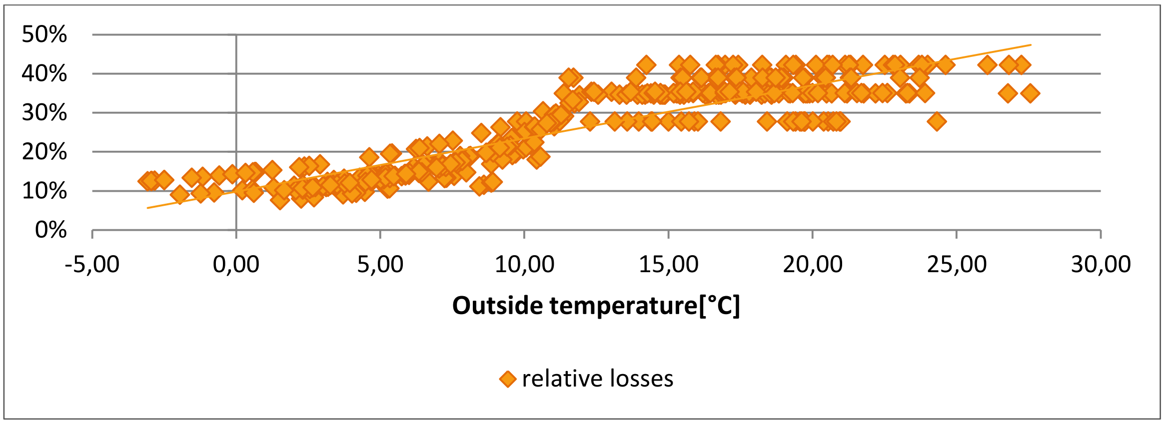

Figure 29: Relative losses in relation to the outside temperature for the DH network Stetten

The DH networks of Vauban and ZO (Zentrum Oberwiehre) (both within the city of Freiburg), have optimization opportunities, as their total losses at nominal return temperatures lie above the values the grids and the plants should have. A detailed description of these two grids will be disregarded here; information on the most important grid characteristics can be obtained from Table 8.

As stated by the cited literature in the previous chapters, the total thermal losses increase with lower line heat densities. The values of the analyzed grids are summarized in Figure 30. It also includes the values for the additionally lost energy which are going to be discussed within the following subchapters.

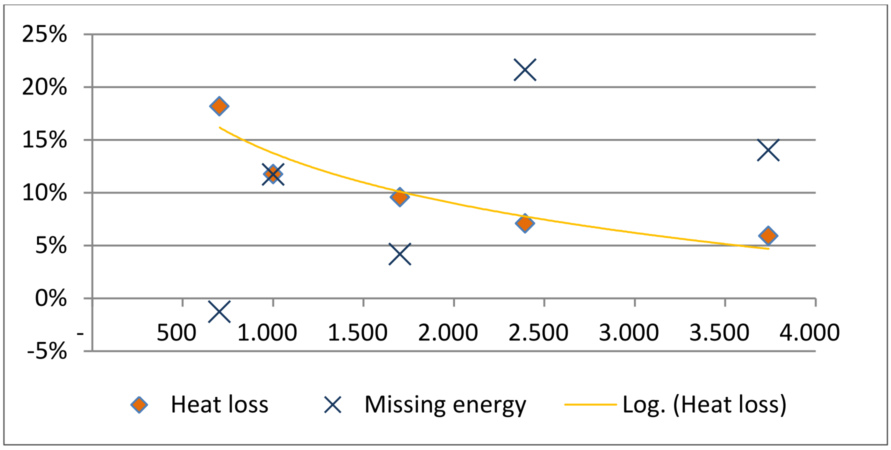

Figure 30: Relative thermal losses with all analyzed networks as well as the deviation of effective fuel input and the theoretical one

For the lack of information on real operation temperatures, the following analysis aims at figuring out which temperature levels the networks are likely to have. Based on a simulation of varying return temperatures, loss values and associated cost saving potentials as well as emissions are determined, followed by a discussion of possible optimization measures.

8.3 GRID PERFORMANCE - AT VARYING RETURN FLOW TEMPERATURES

The Excel calculations evaluate the grid performance on the basis of several return flow temperatures. While the supply temperature can easily be influenced by the system operator and follows a clear predetermined gradient related to the ambient temperatures, four theoretical temperature levels for the return temperature shall be discussed in the following[3].

1. A successful heat extraction down to the stipulated flow temperatures (TAB).
2. An even more efficient heat extraction falling below the TAB values (TAB – 15°C).
3. An exceeding temperature level compared to the TAB by 10°C.
4. An exceeding temperature level compared to the TAB by 20°C.

As can be drawn from Figure 31, relative losses will increase with higher return temperatures. While this is not surprising, as losses directly correlate to the medium temperature, most of the grids show higher overall losses than caused by the theoretical losses of the grid. This means that excessive return temperatures cannot be the only reason for deficient network efficiencies.

Olsen et al. (2008, p. 7) estimate that real heat losses could be 20-30% higher than the theoretically determined values. Pipe ages or low efficiencies of the plants are other possible reasons for exceeding the norm.

For Vauban being a rather new grid, aging of the pipes is unlikely to cause additional losses and 2% additional losses can be explained by the calculation deviations and applied assumptions, which certainly do not completely match reality.

With Stetten it seems that the stipulated return temperatures are met or even fall below and that other grid parameter work optimally as well. Still, the overall thermal loss, caused by the low line heat density, is an issue which should be tackled (see chapter 7.2). Landwasser and ZO have rather low nominal thermal losses. Landwasser is an aged grid which most probably has lost insulation capacities and therefore increased heat conductivities which could lead to the large discrepancy between real fuel input and theoretically demanded energy to cover sales and losses. The relatively new DH network of ZO most probably has a problem with the heat generation units. Theoretically, relative losses should not exceed an average of 4 % with ideal heat extraction and 8.5% with high return temperatures; however in this case they sum up to approximately 27%.

[3] *TAB stands for the German abbreviation for the technical connection regulations.*

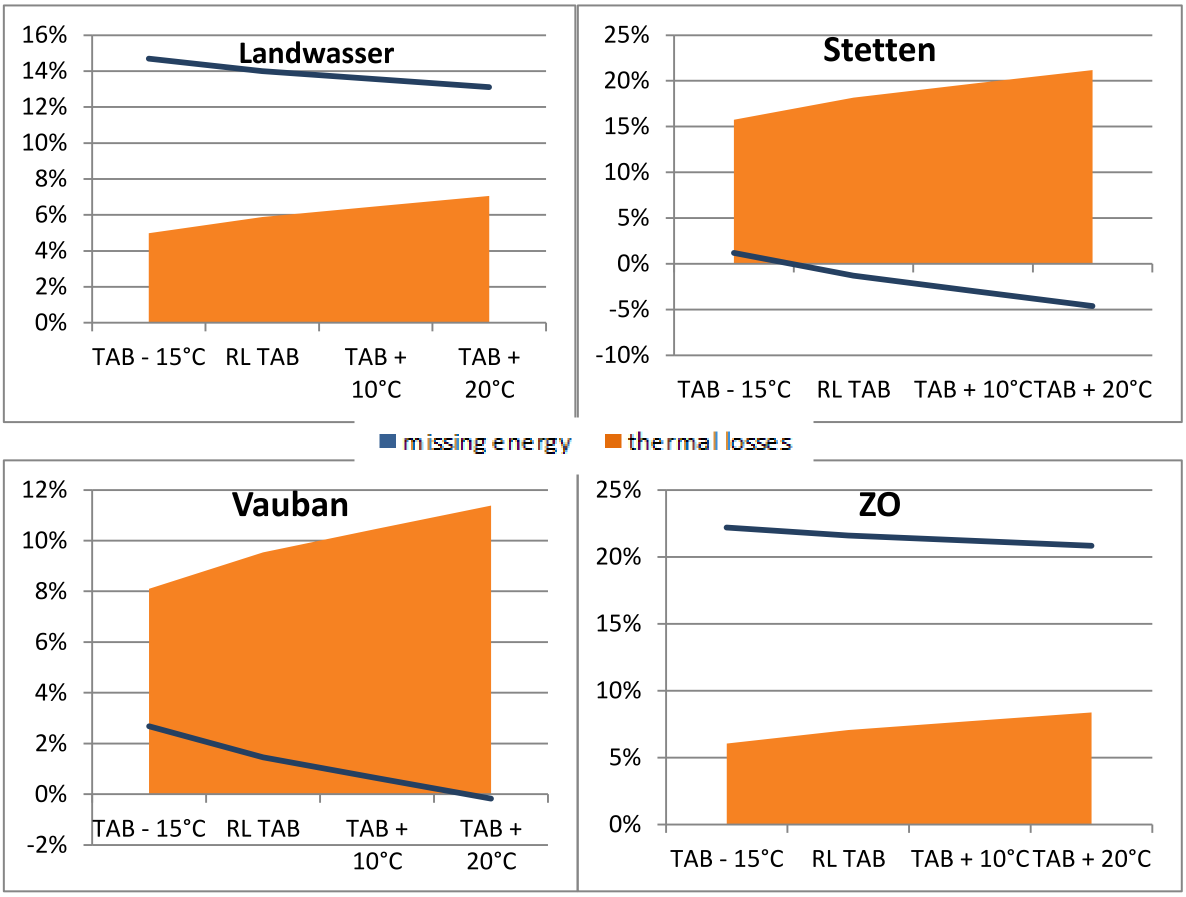

Figure 31: Discrepancy between theoretical thermal losses related to the existent pipes and additional losses, varying with different return temperature levels

Figure 32 shall illustrate the applied calculation approach facilitating the understanding of the described results, similar to Figure 28 on the basis of the ZO network.

With the last bar on the right another operation temperature was modeled. As will be discussed in the following sub-chapter certain measures which could be applied in the future in order to optimize operation and/or in order to counteract the effects of demand reductions are proposed by various experts. Before highlighting additional possible future adjustments on the societal and political level, in a final discussion, the technological options which can actively be approached by WärmePlus and which are not only theoretical measures are briefly introduced at this part of the report and directly applied in the subsequent calculations. A reduction of the overall operation temperature as shown in Figure 32 is one example. The applied temperature levels would be around 60 °C to 40°C in the winter season and 40°C to 20°C in the summer months. As shown in the graph, total losses could be cut to almost half the level, possibly reached with today's set return temperatures.

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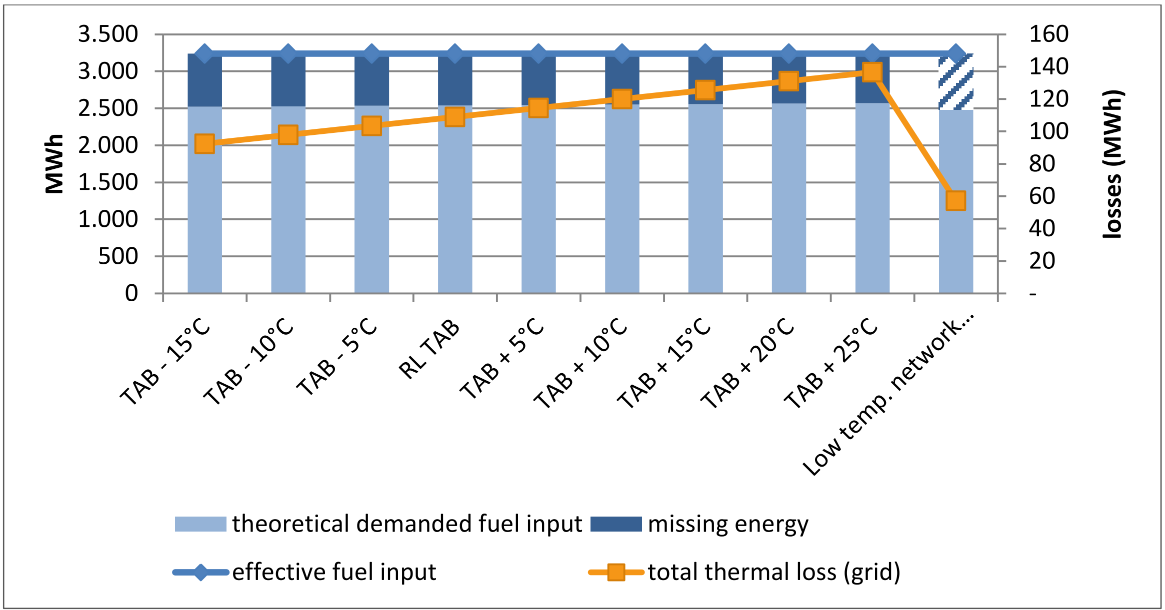

Figure 32: Comparison between the effective fuel input and theoretical demands for sales and thermal losses for the DH network ZO – at varying return temperature levels

Proposals for technological improvements

With technological and organizational optimization measures an increased return on investments is strived for. As stated before, Wolf and Jagnow (2011, p. 10) question the future of DH and also the benefit of current funding options which support CHP units and large solar thermal installations in combination with district heating networks, in areas with either new or insulated houses and hence a low heat demand. Many other studies, however (e.g. (Knierim, 2007; Zinko, et al., 2008; Olsen, et al., 2008)) show that there are opportunities for a profitable grid operation, even in networks with low heat density.

These latter researchers are supported by the strategic research center for the advancement of a “4th Generation of District Heating Technologies and Systems” (4DH). The coalition of several universities as well as energy companies still sees a “significant green growth potential” (4DH, n.D., p. 1) for the DH sector. In carrying out a holistic research approach, which started in 2012 and goes on until 2017, the research center deals with the assumption that DH will still play an important role in the future, but that technological innovations need to be achieved in order to maintain the many benefits this technology can provide (4DH, n.D., p. 2)

TEMPERATURE LEVELS FOR CURRENT AND FUTURE SUPPLY TECHNOLOGIES

In order to run DH plants as economical as possible the potential temperature reduction has to be exploited optimally, mainly being a question of consumer’s observance of the contract as shown in chapter 7.1. With today’s existing components (radiators, heat exchangers, pumps) this would be easily manageable, however difficult to control.

Olsen et al. (2008, p. 1) as well as the strategic research center 4DH (n.D., p. 3) state that besides optimizing existing grids, in terms of better heat extraction at the consumer’s substation, existing grids need to be changed to, and new grids need to be constructed as low temperature networks (50-60 °C supply temperature – and a bit higher during winter), having well insulated small dimensioned twin pipes, suitable for low-energy houses, ideally within the next 10 years. This will guarantee a reduced heat loss and therefore higher cost effectiveness. Low temperature DH grids provide the same comfort with lower primary energy consumption and lower resource consumption levels lead to lower emissions (Dalla Rosa, et al., 2011, p. 2407). These new temperature levels can be used within new buildings with lower heat demand and are compatible with floor heating and in-wall systems (Euroheat & Power, 2012, p. 20).

The new temperature levels would also provide the opportunity to include low temperature heat generators such as solar thermal units or heat pumps (UM Ba-Wü, 2011, p. 53).

With the energy carrier being below demanded temperatures for hot water, the question arises how the breeding of legionella shall be prevented. The 4DH proposes to apply "highly efficient compact heat exchangers with a very small volume of DHW (domestic hot water) in the pipes to the tap; and UV-sterilization of the water entering and circulating in the DHW system of buildings" (4DH, n.D., p. 6). Dalla Rosa et al. (2011, p. 2408) mention short pipe lengths as an additional measure to prevent water impurities as well as for guaranteeing required temperatures of hot water.

PIPING NETWORK

As discussed in chapter 7.1 and shown above, older DH grids have aging pipes which can have largely increased thermal conductivity and therefore heat losses (Euroheat & Power, 2012, p. 13). Efficiency could be improved and carbon emissions lowered by pipe replacements. It needs to be assessed in each individual case if these measures pay off. With a lifetime of about 30 to 50 years (Wolff & Jagnow, 2011, p. 41; Perpar, et al., 2012, p. 197) it would definitely be worth an examination.

Moreover pipes (just as plants) have often been planned oversize according to Zinko et al. (2008, p. 65) partially because prospective expansion needed to be considered. Today, however, planning a new grid for low-energy houses can be carried out on the basis of smaller pipes which have lower thermal losses. Zinko et al. (2008, p. 65) propose the rule "as slim as possible", because demands continue to drop, offsetting potential additional connections. Also with the achievement of more efficient heat extraction, dimensions of the pipes could be smaller as mass flow would decrease. In case of few critical hours, for which pipes could be too small, booster pumps or individual storage tanks /could compensate for low dimensions (Zinko, et al., 2008, p. 65).

8.4 CONTINUATION OF THE GRID ANALYSIS

Besides the modeling of the low temperature network also effects of possible grid renovations were evaluated. Furthermore alterations of potential demand reductions (by 50%) were analyzed. It shall be reminded, that the two energy demand values, space heat and hot water, will develop differently in the future. While hot water demand will more or less stay constant, demand reductions will only apply to space heat demand (Wolff & Jagnow, 2011, p. 36).

Figure 33 depicts losses at varying return temperature levels on the basis of the mentioned heat demand reductions as well as a theoretical drop of the overall operation temperatures and a theoretical substitution of the grid to high standard twin pipes.

Even though investments for existing grids would be very high if the pipes would be changed – and for most cases not realistic, the comparisons of the scenarios can provide valid information for prospective grids in areas with low heat demand density.

Regarding the upper lines (demand reduction scenario), relative thermal loss increases as total losses stay constant if the grid stays the same For the fact, that only space heat demand decreases, relative losses do not double. It can be drawn from the graphs that if there is a demand reduction in one of the networks, it gets even more important to reach stipulated return temperatures. When a low temperature grid is installed, relative losses will be almost the same to TAB vales with current temperature levels.

The example of grid renovation (in this case complete substitution) with optimally insulated twin pipes shows that losses could be lowered considerably in all of the grids.

The following cost evaluation shows that some grid renovation investments could pay off.

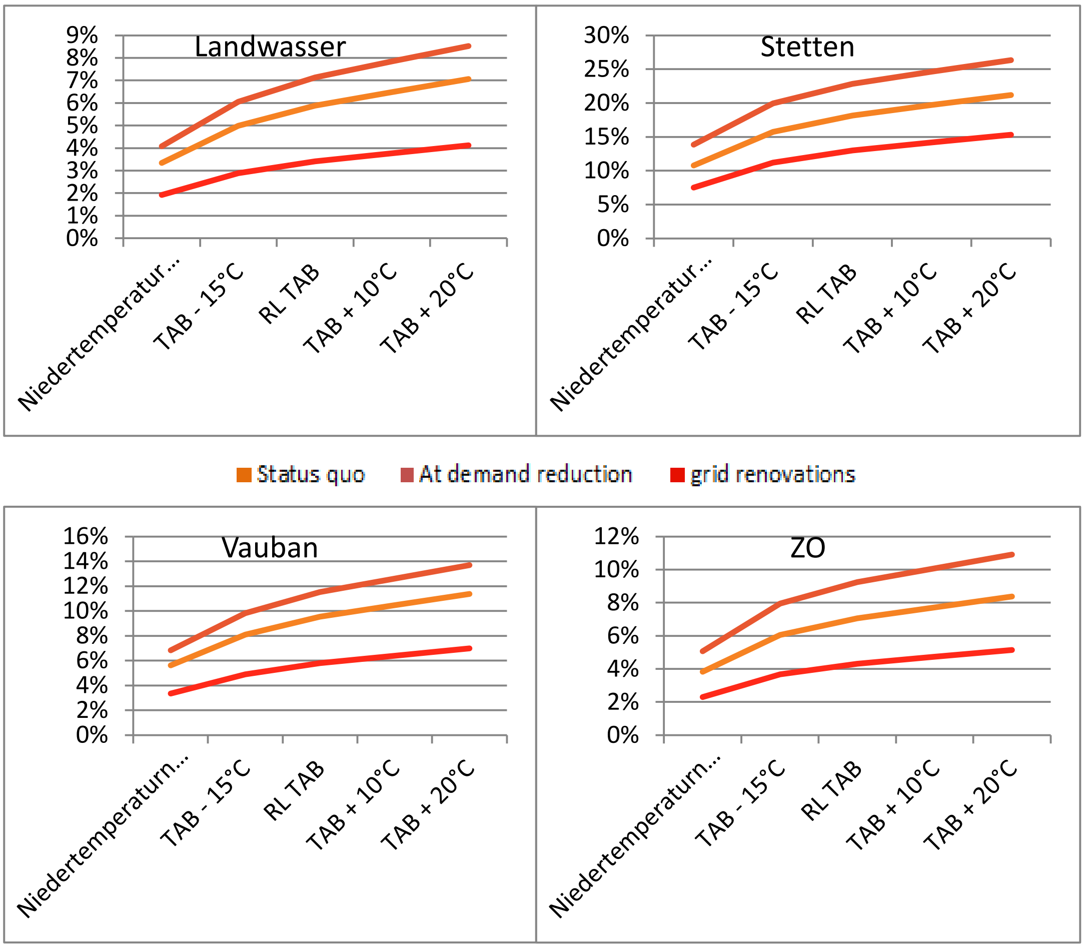

Figure 33: relative losses for current heat demand values, at 50% demand reduction and with a theoretical grid substitution, with high standard twin pipes

9 COST EVALUATION

Table 9 shows the effects of varying operation temperatures on fuel expenditures. It summarizes fuel costs for the four chosen grids for the investigated return temperature levels. It compares total annual costs of the determined demanded energy, the real fuel input and the theoretical fuel input with lowered thermal losses due to grid substitution (which obviously implicate large investments). Figure 34 illustrates the same values graphically. When looking at the graphs it needs to be considered that the scales are distinct.

Table 9: Fuel costs for the four analyzed DH grids – for the effective and a theoretically demanded fuel input, as well as for the networks with a theoretical grid substitution

	Landwasser			Stetten			Vauban			ZO		
Costs in t €	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
Low temp.	2,457	2,066	2,045	198	186	182	519	495	487	91	69	69
TAB - 15°C	2,457	2,096	2,064	198	196	188	520	506	494	91	71	69
TAB	2,457	2,113	2,074	198	200	191	520	512	498	91	71	69
TAB + 10°C	2,457	2,124	2,081	198	204	194	520	516	501	91	71	70
TAB + 20°C	2,457	2,135	2,088	198	207	197	520	520	503	91	72	70

1) Real fuel input; 2) Demanded energy; 3) Renovated grid

The values show that costs obviously vary at different return temperatures, as more fuel needs to be combusted in order to compensate for the higher losses. The same holds true for the comparison of the theoretical costs with a renovated grid; total fuel costs would be lower than with the current grid. This difference; however is rather low with all four grids and would not justify renovation measures. When looking at the costs for the additional losses (see Figure 31) which in the case of Landwasser are likely to be caused by increased thermal losses due to aging of the pipes, a much larger cost saving potential becomes obvious. As discussed in the introduction of the grids only in the case of Landwasser the additional losses can be assigned to this reason. For ZO which also has very high additional cost levels (relative to the costs caused by the demanded heat) as well, other possible causes like the heating unit need to be checked.

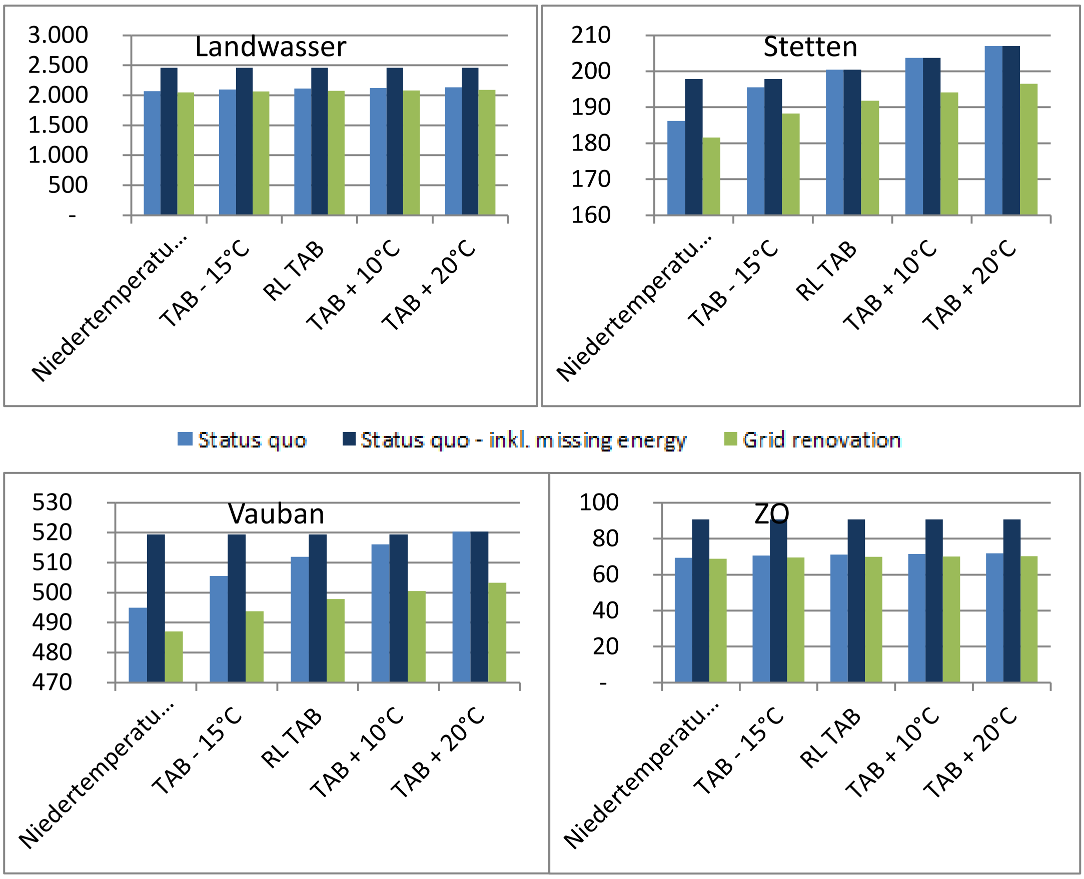

Figure 34: Graphical representation of different fuel costs – for the effective and a theoretically demanded fuel input, as well as for a theoretical grid substitution in (thousand Euro)

In regards of the large total costs saving potential in the case of Landwasser a NPV calculation was carried out. While the total cost saving potential is about € 400,000 each year, three cost saving levels were looked at as the available data do not guarantee that the total missing energy can be ascribed to the aged grid.

9.1 INVESTMENT ANALYSIS FOR GRID RENOVATIONS

The analysis assumes that the total grid is replaced. Based on approximate cost values, presented by Wolff and Jagnow (2011, p. 23), who refer to a study done by the AGFW, an average cost value of € 500 for each meter grid was taken. These average costs seem to be on the upper scale of investment costs. In the case of Landwasser this would mean a total investment of € 3.82 million. This investment cost is contrasted to the three analyzed fuel cost saving potentials of € 200,000, € 300,000 and maximum €400,000.

The calculations only aim at an understanding of the relationship between investments in the grid and the resulting potential cost savings. It does not reveal any information about the general cost efficiency of the grid. This question shall be dealt with in a following step, on the basis of a fictional grid.

Assuming an investment period of five years and a total project period of 20 years, and discount rates between 3% and 12% the following results, presented in Table 10 and Figure 35, hold true.

When looking at the results, the major role of the discount rate which is highlighted in the methodology chapter becomes obvious.

Table 10: NPV values for investments in grid substitution (Landwasser) depending on varying annual fuel cost savings and varying discount rates

	Discount rate	3%	6%	9%	12%
Annual savings	Investment	-3,494,317 €	-3,214,034 €	-2,967,804 €	-2,750,444 €
200,000 €	Total savings	2,975,495 €	2,293,984 €	1,825,709 €	1,493,889 €
	NPV	-518,822 €	-920,049 €	-1,668,607 €	-2,000,428 €
300,000 €	Savings	4,463,242 €	3,440,976 €	2,738,564 €	2,240,833 €
	NPV	968,926 €	226,943 €	-229,240 €	-509,611 €
400,000 €	Savings	5,950,990 €	4,587,968 €	3,651,418 €	2,987,777 €
	NPV	2,456,673 €	1,373,935 €	683,614 €	237,333 €

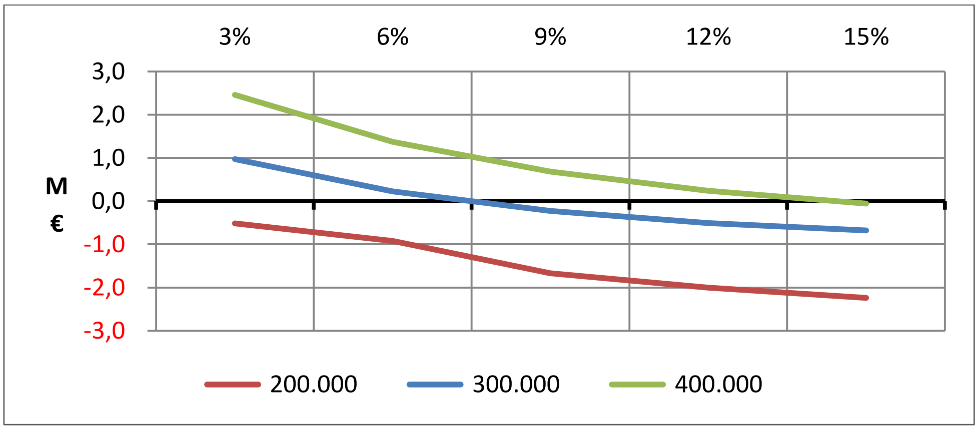

Figure 35: Graphical representation of different NPV values for investments on grid investments depending on different annual fuel cost savings and varying discount rates (for Landwasser)

With an applied discount rate of up to 6%, the NPV will be positive if savings sum up to € 300,000; with an exploitation of the total cost saving potential, a total grid substitution would be profitable for all applied discount rates.

The same analysis was applied for the other four grids. As Vauban and ZO are not likely to have issues with the pipes the calculations shall only briefly illustrate how much money could be invested in general if aiming at a exhaustion of the above determined cost saving potential. As these are only comparably little cost saving potentials, profitable investments cannot be very high. With Vauban for example a positive NPV would only be gained with maximum investments of € 300,000 and annual savings of € 20,000, which corresponds to the maximum cost saving potential of the grid (see Table 9). With Stetten, thermal losses will stay at a high level, as long as the line heat density stays at the low level (which will not change in the future), and any renovation measures will hardly lead to cost savings. For the ZO network, figures are similar to Vauban; as the grid is much smaller however, the relative saving potential is much higher.

VOLUME FLOW

As described in chapter 7.1, varying return temperatures have a great effect on the demanded volume flow, and thus on the pumping expenditures which constitute an important cost factor. As data on pumping costs were of poor quality, no reference values (kWh_{el}/kWh_{th} at TAB) were available; however the great differences of up to 300% of demanded volume flow show the importance of sticking to the compulsory heat extraction efficiencies. Considering the fact, that higher volume flow also causes more friction and pressure losses, the increase of pumping effort even exceeds the relative increase of the volume flow.

Table 11: Volume flow depending on the return temperature (in total numbers (1000 m³) and in % in relation to TAB)

Volume flow (1000 m³)	Landwasser	Stetten Süd	Vauban	ZO
TAB - 15°C	457.8 (-29%)	76.4 (-32%)	190.0 (-30%)	24,4 (-30%)
TAB	644.8 (-)	113.2 (-)	270.1 (-)	35.0 (-)
TAB + 10°C	895.9 (+39%)	169.1 (+49%)	378.5 (+40%)	49.3 (+41%)
TAB + 20°C	1,531.9 (+138%)	374.7 (+231%)	653,8 (+142%)	85.2 (+144%)

9.2 INVESTMENT CALCULATIONS FOR A FICTIONAL DH NETWORK

Until this point of the study, the analysis was done in order to evaluate the present performance of several DH networks of WärmePlus. While this is the main purpose of the research question as well as an assessment of possible future optimization measures, a rough evaluation of the presented determining factors for a profitable operation shall be applied in a comparison of the overall socio economic profitability of a DH network to individual installations.

9.2.1 FRAMEWORK STIPULATION

The evaluation shall take place on the basis of the Vauban DH network area, with imaginary consumption pattern and other variable factors, though. Investments for several connection ratios and resulting grid lengths, coming down to a scenario with only individual boilers, are compared. A standardized, relatively densely built neighborhood was assumed where each flat has 100 m², and an average of 20 flats form one housing unit, supplied with one central heating unit (in case of individual boilers).

Figure 36 depicts the area under investigation. The green buildings are currently connected ones, the red ones would add with a 100% connection ratio. When adding the additional houses, higher grid investments would apply, with only slight differences with the distribution network and supply pipes being proportional to the connection ratio. The calculations are based on a 100%, 70% (as it is with Vauban), 40% and 0% connection ratio. In the last case all the buildings and within the other scenarios the remaining shares would be powered individually.

It was decided to apply an average pipe diameter of DN 80 of twin pipes with high insulation standard and for comparison a single pipe type with DN 100 and low insulation standard, for the loss calculations.

Figure 36: Map of the analyzed district, showing 100% connection ratio (green and red buildings) and a 70% connection ratio (only green buildings), as well as the respective necessary grid (orange and red or only orange)

Another varying factor will be the total heat demand, applying demand values for buildings built between 1974 and 1994 (a period where the first insulation standards were set up), and for buildings being constructed in the last years. The first ones will have a total heat demand (space heat and hot water demand) of 130 kWh/(m² a), the latter ones only half the value, i.e. 65 kWh/(m² a). These values were derived from Hausladen and Hamacher (2011, p. 21). Older houses are disregarded as these are more likely to undergo energetic renovations in the next years, influencing the results. Another variable is the medium temperature, influencing the thermal losses. A rather high value (75 °C), which approximately applies to the above discussed grids, a temperature level applying to a successful heat extraction at current technologies (60 °C) and a low medium temperature (35°C) which applies to a low temperature grid, are taken.

All in all, 20 variations of the parameter were created, and these again compared with two different types of pipes and insulation thicknesses. Table 12 and Table 13 present the most important variables, split up into the two categories with high and low heat demand (for space issues, four combinations could not be included in the tables, they are represented in the result figures though). The variable parameters are highlighted in light blue.

While several options of power sources with different resources could be chosen, it was decided on a mix of biomass (wood pellet) boiler and a natural gas (peaking boiler) for the central power source and biomass (also pellet) boilers for the individual installations.

The DH boiler was assumed to work with a slightly higher overall efficiency (85%) than the individual boilers (80%). The capacities were calculated according to the methodology presented in chapter 6.3, whereas the capacity of the DH boilers was downsized by the application of the aggregation factor. The base load pellet boiler is supposed to cover 35% of the heat load in the high demand scenario and 55% at low demand. The capacity is only 25% of total capacity for both scenarios.

9.2.2 LIMITATIONS

For simplicity's sake calculations were carried out without CHP units, as their cost effectiveness is highly dependent on optimal load and electricity prices. This would demand a deeper analysis, based on modeling tools which incorporate the electricity market, but would go beyond the scope of the study.

Another simplification is that calculations do not cover each single technological component of complete central and decentral heating stations. The target of the calculations is to show the effect of varying parameters on the possible profitability of an investment.

As mainly the role of the technological components of the networks as well as the influence of high or low connection ratios and demand shall be highlighted with the calculations, fuel prices were assumed to be constant throughout the project period.

The socio-economic comparison will not include externalities such as environmental and health costs. It only includes the necessary investments as well as O&M costs and considers the lifetime of the different components. Also CO2 quotas costs are not included.

Table 12: Most important grid characteristics at a high energy demand scenario, with varying connection ratios and medium temperatures

	1	2	3	4	6	7	9	10
Connection ratio	100%	100%	100%	70%	70%	40%	40%	0%
Heat demand (kWh/m²a)	130	130	130	130	130	130	130	130
				DH				
Heated area (m²)	203,451	203,451	203,451	142,450	142,450	81,000	81,000	-
Flats	2,035	2,035	2,035	1,425	1,425	810	810	-
Heat sales (MWh/a)	26,449	26,449	26,449	18,519	18,519	10,530	10,530	-
Grid lengh (m)	7,619	7,619	7,619	6,322	6,322	4,957	4,957	-
Line heat density (MWh/m a)	3.5	3.5	3.5	2.9	3.9	2.1	2.1	-
Medium Temp. (K)	75	65	35	75	35	75	35	-
Thermal losses (MWh/a)	2,765	2,212	1,290	2,294	1,071	1,799	840	-
Efficiency losses (MWh/a)	4,255	4,299	4,122	3,123	2,938	1,849	1,705	-
Boiler Capacity (pellets) (MW)	3.21	3.15	3.05	2.29	2.15	1.36	1.25	
Boiler Capacity (NG) (MW)	9.63	9.45	9.15	6.86	6.46	4.07	3.75	-
				Individual				
Flats	-	-		610	610	1,225	1,225	2,035
Heated area (m²)	-	-		61,001	61,001	122,451	122,451	203,451
Remaining heat demand (MWh/a)	-	-		7,930	7,930	15,919	15,919	26,449
Efficiency losses (MWh/a)	-	-		1,586	1,586	3,184	3,184	5,290
Boiler Capacity (MW)	-	-		5.6	5.6	11.2	11.2	18.7
Total costs for consumers (t€)	- 20,065	- 20,065	- 20,065	- 22,355	- 22,355	- 24,661	- 24,661	- 27,701
NPV for DH operator (t€)	2,976	3,137	3,407	1,777	2,135	588	868	-
NPV for DH operator (t€) without scrap value	1,26	1,425	1,695	357	714	- 526	-245	-

Table 13: Most important grid characteristics at a low energy demand scenario, with varying connection ratios and medium temperatures

	11	12	13	14	16	17	19	20
Connection ratio	100%	100%	100%	70%	70%	40%	40%	0%
Heat demand (kWh/m²a)	60	60	60	60	60	60	60	60
DH								
Heated area (m²)	203,451	203,451	203,451	142,450	142,450	81,000	81,000	-
Flats	2,035	2,035	2,035	1,425	1,425	810	810	-
Heat sales (MWh/a)	12,207	12,207	12,207	8,547	8,547	4,860	4,860	-
Grid lengh (m)	7,619	7,619	7,619	6,322	6,322	4,957	4,957	-
Line heat density (kWh/m a)	1,602	1,602	1,602	1,352	1,352	980	980	-
Medium Temp. (K)	75	65	35	75	35	75	35	-
Thermal losses (MWh/a)	2,765	2,212	1,291	2,294	1,071	1,799	840	-
Efficiency losses (MWh/a)	2,246	2,162	2,205	1,626	1,443	999	855	-
Boiler Capacity (pellets) (MW)	1.65	1.59	1.48	1.19	1.06	0.73	0.63	
Boiler Capacity (NG) (MW)	4.94	4.76	4.45	3.58	3.17	2.20	1.88	-
Individual								
Flats	-	-		610	610	1,225	1,225	2,035
Heated area (m²)	-	-		61,001	61,001	122,451	122,451	203,451
Remaining heat demand (MWh/a)	-	-		3,660	3,660	7,347	7,347	12,207
Efficiency losses (MWh/a)	-	-		732	732	1,469	1,469	2,441
Boiler Capacity (MW)	-	-		2.58	2.58	5.19	5.19	8.62
Total costs for consumers (t€)	- 10,848	- 10,848	- 10,848	- 11,428	- 11,428	- 12,014	- 12,014	- 12,785
NPV for DH operator (t€)	1,498	1,658	1,924	744	1,098	2	279	-
NPV for DH operator (t€) without scrap value	- 214	- 54	212	- 677	- 322	-1,112	- 835	-

Table 14: Various constant parameter (costs e.g.) applied for the investment calculations

Discount rate	6.0%
High heat demand (kWh/m²a)	130
Low heat demand (kWh/m²a)	60
Heat price - for high demand (€/kWh)	0.065
Heat price - for low demand (€/kWh)	0.075
Gas price for W+ (€/kWh)	0.037
Pellet price for W+ (€/kWh)	0,035
Pellet price for indiv. (€/kWh)	0.047
Full load hours	1700
Aggregation factor	65%
Capacity share pellet boiler	25%
Load share pellet boiler (high demand)	35%
Load share pellet boiler (low demand)	55%
Boiler efficiency (DH)	85%
Grid investment (€/m)	400
O&M grid	2%
Cost Boiler W+ (€/MW) (DH)	100,000
O&M Boiler W+ (€/MW) (DH)	4,000
Boiler efficiency (ind.)	80%
Cost ind. boiler (€/MW)	170,000
O&M ind. Boiler (€/kW)	6.3
Substation Cost (€/unit)	2,000
O&M Substation (€/unit)	150
Project period (yr)	20

** Investment and O&M costs were derived from* (EnergiNet.dk, 2012).

While the Tables above present the most important consumption and operation variables, Table 14 lists the universally applied values, mainly costs and fuel distribution.

The two tables (Table 12 and Table 13) show clear differences between the different scenarios caused by different heat demand values of 60 and 100 kWh/(m² a), varying connection ratios of 100, 70, 40 and 0% and by different medium temperature levels of 75, 65 and 35 °C.

While the connection ratio defines the total connected space and the demanded grid length the inclusion of the heat demand per m² determines total heat demand, sales and thus line heat density. While these values are constant within the same connection ratios and space dependent heat demand, the variation of the medium operation temperatures again has influence on the grid dependent losses and thus the overall fuel consumption and the total boiler capacity.

As the grid expansion is not proportional to the connection ratio, the line heat density is considerably influenced and obviously goes further down, with lower connection shares. Relative losses increase in this case.

Concerning individual installations, the maximum demanded boiler capacity is much higher than the maximum DH heating boiler capacity. This is caused by the aggregation factor, although the DH supply unit has to make up for the grid dependent thermal losses.

Figure 37summarizes the energy flows for each single scenario.

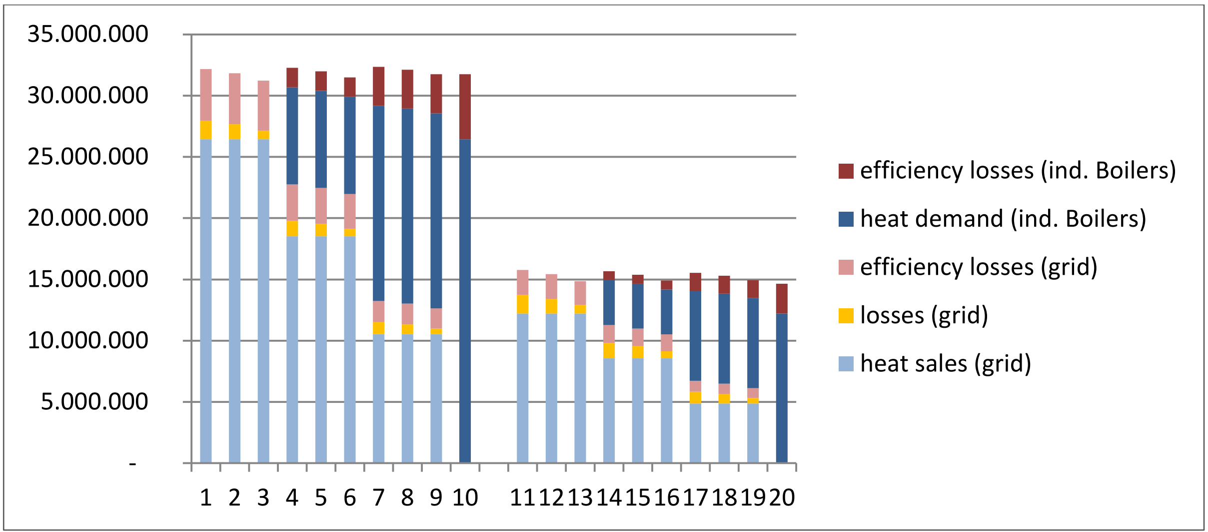

Figure 37: Representation of the demanded energy distributions for 20 different scenarios

9.2.3 COMPARISON OF TOTAL HEATING COSTS AND NPV VALUES

The economic evaluations are regarded from two different points of view. The first result is the total socio economic cost for the consumers, for each single combination of the introduced parameters.

The three bottom rows of Table 12 and Table 13 summarize the total costs for consumers and the NPV values for varying investments in the DH network for the DH operator.

The individual costs consist of the total investment costs in the individual boiler capacity and the substations (in case of DH connection) and of the O&M costs for these, including the fuel costs and the costs for the purchased heat (in case of DH connection).

The NPV values for the DH operator comprise the total investment costs in the grid and the boilers, their O&M costs including the fuel purchase costs. Evaluations are done twofold: including and excluding the scrap value of the grid, which is subtracted from the investment costs (as shown in the NPV formula in the methodology chapter). Values are derived based on the variables listed in Table 14.

Based on the stipulated assumptions results show that from the consumer's point of view DH will be the cheapest option for both high and low heat demand scenarios, with 100% connection ratio. Although pellet prices per kWh are much lower than the heat price with a DH connection, the great investments in the boiler capacity result in higher costs. Results are not influenced by the heat extraction performance, as this is not included in the price for each extracted kWh of the grid (with current billing concepts).

Also in regards to the NPV for the DH operator, the highest connection ratios are the most cost effective ones. Larger investments in the grid and increasing losses are offset by higher heat sales. Concerning the low demand scenario NPV values are generally lower and positive values can only be achieved with high connection ratios. With the high demand scenario, NPV values are positive with all connection ratios. At lower rates, however, values are little. These observations only hold true, when including the scrap value for the DH grid, after the project period. When this value is disregarded, results appear to be different. While the consumer has no cost impact with varying temperature levels, the effect of low medium temperatures can be observed within the NPV values for the DH operator.

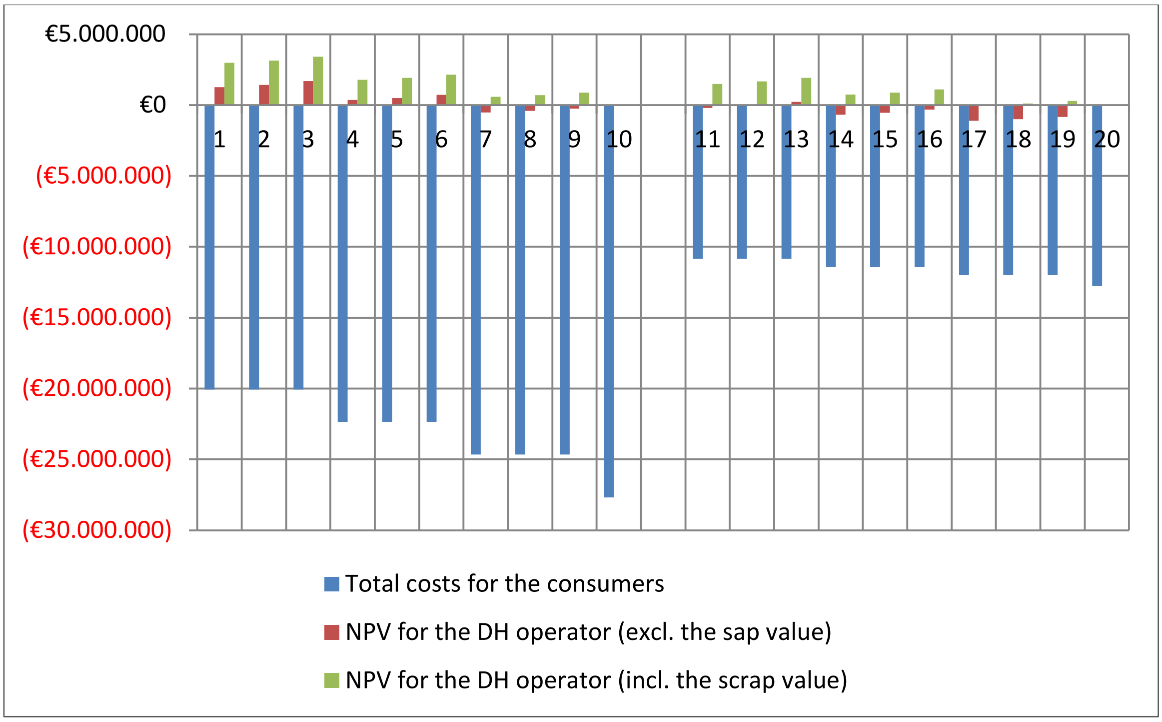

Figure 38: Total socio economic costs as well as NPV values for the DH operator for all analyzed scenarios

Due to the different scale, the differences caused by the temperature variations and thus altered thermal losses become more apparent, when looking at Figure 39 and Figure 40. The inclusion or exclusion of the scrap value has still the greatest impact on the level of NPV; but differences due to heat extraction performance are more than notable and can even be essential in some cases.

As demanded by Olsen et al. (2008, p. 1) as well as by 4DH (n.D., p. 3) ideally well insulated smaller dimensioned twin pipes shall be applied in the next years. The figures thus also present different results for altered pipe diameters and insulation standards. Investment costs have been assumed to be similar. While twin pipes generally have higher material costs, their installations can be cheaper, as described in chapter 7.3 (Zinko, et al., 2008, p. 65).

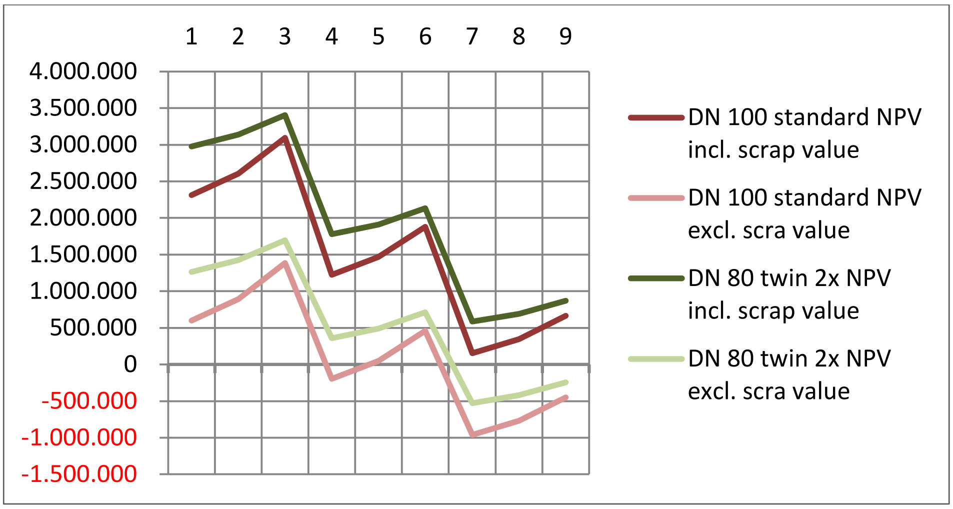

Figure 39: NPV at the high demand scenario, for selected pipe diameters and insulation standards – including a scrap value for the grid.

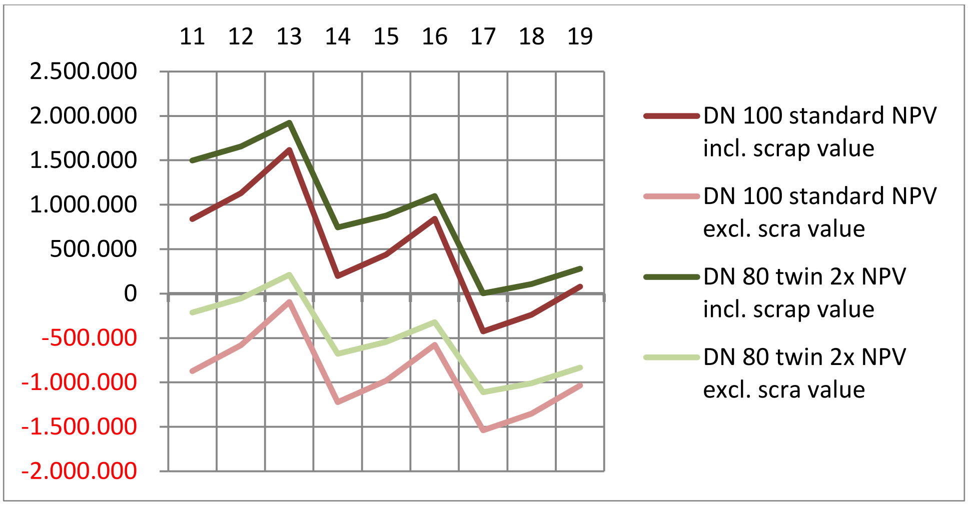

Figure 40: NPV at the low demand scenario, for selected pipe diameters and insulation standards – including a scrap value for the grid.

To finalize the investment calculations, a small scale sensitivity analysis was done on the basis of changing gas prices and increasing heat prices. The threshold value of natural gas prices for a positive NPV value for the DH operator is set to € 0.05. Concerning the lower costs of the DH scenario for consumers, prices per kWh heat could be increased from € 0.065 up to € 0.09 in the high demand scenario and from € 0.075 to up to € 0.086 in the low energy demand scenario, until individual boilers become cheaper compared to DH connections, assuming a constant price level for biomass.

10 DISCOURSE ON POSSIBLE CHANGE

Important issues like the political framework influencing the societal acceptance of DH cannot directly be influenced by badenova and can thus not be regarded as possible measures the company needs to undertake in order to optimize the performance of its grids, as asked in the second part of the research question. Still the approach of the mentioned issues is seen as being crucial in order to overcome the determined challenges for a future expansion of the technology as well as to improve the cost effectiveness of current and future DH grids.

10.1 BEHAVIORAL CHANGE

Even though decisions on heating systems and its fuels are not an every-day decisions, installations are dependent on consumer's choices unless they are predetermined by planners or politicians. Needs and concerns relating to heating technologies have been introduced in chapter 7.5; it is shown that consumers are quite reluctant concerning changes.

The mentioned fear that customers will be dependent on the DH network operator is discussed in the handbook on DH of the Economic Ministry of Baden-Württemberg. The authors do not disagree on the argument that a certain dependency is created with a DH network; however it is pointed out that it could terminate the existing dependency from fossil fuel imports which cause an impaired balance of payment. Besides local trade and regional timber industry e.g. could be supported. It is also highlighted that the operator cannot simply increase prices, as the contract includes a predetermined price escalation clause. With water and electricity supply dependency is taken for granted and not an issue. It is said, that it just seems to be a matter of habits (MWi Ba-Wü, 2007, p. 37).

Almost all (95%) energy related behavior depends on habits, provided that economic circumstances are not obviously privileging one option Opinions and habits are "shaped by individual context and (are) formed by past experiences, as much as by the knowledge and information that consumers have access to" (Egmond & Bruel, 2007, p. 6). Disrupting this circle of socio-technological lock-in is said to be very difficult (Upham & Jones, 2012, p. 22). This might explain why DH has kept on having similar shares in the heating sector for years in Germany and stay low on a global scale.

Egmond and Bruel (2007) deal with the issue of how energy related behavior could be influenced. The following paragraph shall give a brief overview of their results:

Behavioral change is achieved by making consumers aware of their habits, removing incentives which contribute to its repetition and providing positive alternatives (Egmond & Bruel, 2007, p. 7). Considering this, it can be concluded that providing subsidies without also additionally rise taxes on unsustainable solutions will not interrupt habits and contribute to new behaviors.

Policy interventions rather need to be a mix of spreading information and knowledge (predisposing factors), paired with providing economic incentives like subsidies as well as introducing higher taxes, i.e. pricing externalities and providing skills (enabling factors). As soon as rewards or any other positive feedback is gained (reinforcing factors), the repetition of the behavior will be more attractive, when a similar decision is required. The habitual behavior can thus be "unfreezed" and shifted to a sustainable new, planned behavior (Egmond & Bruel, 2007, pp. 7, 11, 13).

The authors also point out the importance of the availability of knowledge and infrastructure (Egmond & Bruel, 2007, p. 7). In the present case, the company WärmePlus is one of the available resources, offering the needed services. Therefore publicity is important for the company, so that the population gets to know the company and its services. It is also said to be a good idea if a municipality approaches the population, as people are likely to assume that the company is only trying to make a profit (MWi Ba-Wü, 2007, p. 34).

10.2 POLITICAL CHANGE

Several countries like Denmark, Finland or Russia have managed to achieve a 30-50%. CHP share in electricity generation and have expanded DH considerably. Their common efficient electricity and heat generation could be developed by a focused, thoughtful and well-implemented policy and has not been arrived at by chance (IEA, 2009 b, p. 11). It is the result of decisions made by politicians and planners during the last few decades. During the 1970s and 1980s, taxes were applied to fuels used in heat generation with the objective of encouraging the use of environmentally friendly energy and efficient energy utilization. Biomass and biogas were exempted from taxes (ENS, 2005, p. 16). Energy consumption has fallen since 1980 even though the floor area being heated has increased and biomass resources as well as waste incineration constitute important pillars for covering the remaining energy demand. The co-generation of heat and electricity has replaced the electricity which previously was produced at less environmentally friendly electricity only condensation plants and in 1997 Denmark managed to become energy self-sufficient. (ENS, 2005, p. 12).

This clear long lasting strategy has contributed to a widely accepted holistic energy policy.

It is not sufficient only to provide supportive legislation to foster a certain investment climate. “CHP (e.g.) does not only need substantial financial incentives to make it happen” (IEA, 2009 b, p. 17), it is rather equally important to eliminate hindering factors, in order to promote a certain consumer behavior. Secure and fair prices for CHP electricity paired with regulatory rules relating to connection regulations, socio-political issues, relating to public knowledge of CHP benefits have to be given (IEA, 2011, p. 27).

The following Table 15 lists five policy fields which can be applied in order to overcome barriers and actively support CHP development. This is followed by a brief analysis, discussing which of these policies are already implemented in Germany and where there is still scope for improvements (IEA, 2009 b, p. 18).

Table 15: Various policy measures which potentially support a sustainable energy development (based on: (IEA, 2009 b, p. 18))

Policy type	Examples	Existent in Germany or other country?	Positive examples (or possible measures)
1. Financial and fiscal support	Investment and operational support	existent	REA and CHP-Act → Feed in tariff for a limited amount of hours and capital support (increased taxes on fuel oil e.g.)
2. Utility supply obligation	Green certificate scheme (market based mechanism)	existent in Belgium	Obligation for electricity suppliers, to sell a certain share of CHP based electricity
3. Local infrastructure and heat planning	Building regulations	existent	REH Act, ENEV → minimum efficiency standards and RE share
4. Climate change mitigation	CO_2 emission allowance limitation	EU emission trading	GHG emission reduction target / market price on GHG
5. Interconnection measures	Interconnection standard / grid connection guarantee	existent	Feed in guarantee (only for limited amount of hours)

As discussed in Chapter 5.1.2, Germany offers most of the proposed regulations.

Some, like capital support (e.g. funding of storage tanks and DH grids) have only lately been introduced in the amended CHP act of 2012, though. Large scale effects still have to be analyzed, and studies do not yet exist. Concerning electricity self-marketing, CHP operators in Germany have experienced great difficulties, whereas Denmark for example has gained experience of more than 15 years in optimizing their CHP plants against the market (Andersen & Lund, 2007, p. 288).

The federal agency of CHP (BKWK, 2012) has published a statement on the current edition of the CHP act, which largely goes in line with experiences gained by WärmePlus. While the BKWK (2012) appreciates most of the changes of the amended CHP act ("measures go in the right direction"), it demands further steps for reaching the 2020 target (BKWK, 2012, p. 1).

Today the German market faces the situation that due to a highly fluctuating feed in of electricity generated by RES like wind and solar power the electricity market has many hours in which it is hardly economical to run CHP plants as prices consequently fall short. As price decline is most crucial in the morning hours when solar power feed in and heat demand are increasing (BKWK, 2012, p. 1), it is difficult to run the CHP units heat driven (when heat is demanded). But as it is also hardly economical to run the units in a current driven mode, much of the demanded load today is supplied by less efficient boilers.

A base-load generation of five to six thousand full load hours, like it has been the case in the last years, can usually not be achieved anymore. This obviously does not only constrain the income of CHP operators like but will hinder the achievement of the 25% target.

The construction of larger plants could offer the same amount of electricity in fewer hours. This would also be an extra argument for DH grids (BKWK, 2012, p. 1).

It should be noted that the support of intermittent RE technologies should go in hand with a strategy of tackling the resulting challenge of grid instability. In order to achieve this, the following measures will be proposed:

1 CHP technology needs to become more flexible in order to extend the grid balancing capacity. The upgrade of CHP plants to extraction condensation plants which are also able to run on an electricity-only modus with high efficiency, could meet the call of the BKWK for further development (BKWK, 2012, p. 1) in order to reduce investments in the disputed very expensive high voltage power lines as well as the construction of large flexible gas power plants that have to step in in times when the thermal storage tank is full and there is no demand for heat.
   In Denmark, the fact that electricity generation has to become more flexible has been acknowledged in allowing the CHP operators to produce either heat or electricity, according to demand. Besides reserve load boilers are existent consuming excess electricity in periods in which electricity market price is low, thereby avoiding uneconomical production of electricity and yet still producing district heat (ENS, 2005, p. 14&30).
2 Financial recognition of the offered stand-by capacity of CHP units with the introduction of a capacity market would be an additional opportunity to support the spreading of CHP plants.
3 Utility supply obligation (USO) as it is applied in Belgium (see Table 15) could create additional demand for CHP based electricity, as electricity suppliers are obliged to buy a certain share of CHP generated electricity in order to resell it to their customers (IEA, 2009 b, p. 22f).

Regarding the great advantages the CHP technology offers, the statement of Andersen and Sorknæs (2011) that “there is a lack of (political) ambitions to include CHP into system services and balancing”, still holds true, even though it refers to the situation before the latest amendment of the CHP act.

10.3 TECHNOLOGICAL INNOVATIONS

10.3.1 NEW LOADS

Issues with high relative losses at low heat line densities are undisputed. Unlike Wolff and Jagnow (2011), however, many studies see a more optimistic DH future. Zinko et al. (2008, p. 1) for example analyze opportunities to expand networks or find new markets, in order to counteract decreasing demands. Losses need to be compensated in regions where energy conservation measures take place and thus put DH operation below economic threshold.

Nearby houses which are not connected to the grid and which potentially need to substitute their boiler are good options in order to undo the demand decline. Besides focusing on new customers the authors see an option for thermal energy replacing electricity, due to an ever increasing demand for electric devices, such as washing machines, dish washers, or appliances like air conditioning (Zinko, et al., 2008, p. 2). The Euroheat and Power association states that using thermal energy directly would be much more efficient. Tests have proven that up to 62% of power savings can be achieved by connecting the devices to a DH network, compared to using electricity for heating up the water (Euroheat & Power, 2012, p. 14).

As very few of the 'white goods' (washing machines, dishwashers or tumble driers) are connected to warm water, most machines would need to be equipped by heat exchangers (Zinko, et al., 2008, p. 67).

For DH being responsible for about 10% of the European heat market, Zinko et al. (2008, p. 73) see a sufficiently large market for appliances which are capable of using DH as a power source. Also the DH customers would not be the only ones being interested in these products. Also solar heating applications as well as individual biomass plants represent a growing market possibly benefiting from new loads (Zinko, et al., 2008, p. 85).

10.3.2 SOLAR DH

As mentioned in chapter 5.3, solar thermal appliances are said to have a great growth potential for the future, also as DH power units. While Wolff and Jagnow (2011, p. 60) state that this technology contradicts the concept of DH and CHP, as the power is mainly provided during the summer months when there is low heat demand, other studies investigate how this contradiction can be resolved.

The ESTTP presents estimated cost values for future heat generation based on solar thermal, natural gas or electricity. While in 2007 prices per kWh were very similar price cuts for solar thermal power decreasing by half are expected, while costs for NG and electricity are assumed to double until 2030 (ESTTP, 2007, p. 28). Additionally Heidmann et al. point out that investment costs can be cut to half when setting up large scaled installations. (2005, p. 30).

Until 2005, there have been nine pilot-projects in Germany showing that fuel input for the combined heating units can be cut substantially in some cases (Heidemann, et al., 2005, p. 32). This is achieved by the application of large seasonal thermal storage tanks. Surplus heat of the summer months is stored in the long term storage. Until today costs for these tanks are rather high, though (Heidemann, et al., 2005, p. 37). The AGFW, however points out that these tanks could also provide opportunities for other heat sources like waste heat from industrial processes and offering flexible balancing capacity for biomass CHP (e.g.) considering a continuing expansion of intermittent electricity generation (AGFW, 2012 c, p. 13). It is stated that smart district heating on the basis of solar thermal, CHP and HPs could be the future.

11 CONCLUSION

This present Master's Thesis research has been carried out within the setting of badenova WärmePlus, which is a company providing heating concepts as well as operating heating installations, usually connected to a district heating grid.

While the topic of electricity is in major focus within the discourse of the energy transition, heat generation, distribution, and consumption is only of secondary importance. This holds true even though heat energy demand in Germany amounts to about 25% of the total energy demand. The share within the buildings sector is even 70% (Tzscheutschler, et al., 2007, p. 13). This energy demand can be covered by a great amount of heat technologies and sources. Consumer's preferences but also political demands and fuel price developments will influence individual choices. Besides these influences, decreasing demands, due to DSM measures will alter the market within the years to come.

A changing heat market with decreasing demands on the one hand and with increasing regulations on efficiencies as well as resources on the other hand, paired with the fact that energy systems (electricity and heat) can hardly be regarded separately any longer poses new challenges for companies which plan and operate heating systems. While the heat quantity has been of major importance for many years, increasing focus needs to be put on heat quality as well. This means, that distribution and utilization need to be optimized.

District heating operators will especially be confronted with this change, as relative losses are about to increase with decreasing demands, thus influencing the cost effectiveness of the installations.

Various studies have been conducted resulting in very distinct values of a minimum line heat density; a factor which is often taken for network comparison. Threshold values for a profitable operation reach from 350 kWh/(m a) (Zinko, et al., 2008, p. 9) over 550 kWh/(m a) (Bøhm & Kristjansson, 2005, p. 1301f) to 4,000 kWh/(m a) (Wolff & Jagnow, 2011, p. 20). Being confronted with this huge spectrum, DH planners and operators need to know about factors, which lead to these very different interpretations and which can make off for the low sales values. Thus the following research question was approached during the research:

> **What are the determining factors influencing the cost-effectiveness, environmental compatibility and consumer's acceptability of current and future district heating grids of WärmePlus and what measures can enhance profitability?**

While the research question covers all spheres of sustainability – economic, environmental and social factors – focus has been laid on the economic side, assuming that efficiency improvements will also lead to lower emission values. While there is obviously more affecting the environmental performance of heating systems, like the selection of technology as well as the resource, these considerations were only covered as a side note.

11.1 ANSWERS TO THE RESEARCH QUESTIONS

The answer to the first and the third sub-questions can be summarized as follows. The questions deal with the status quo of the legislative as well as technological framework as well as with prospective adjustments. The answers provide initial information on determining factors, which are then applied to answer the second research question.

Political targets today are on the one hand supporting district heating, for aiming at higher share of CHP electricity generation and subsidizing thermal storage tanks as well as promoting the utilization of RES, which can be processed more efficiently in applying larger scaled heating units; on the other hand however demand side management stipulation, influencing the total heat demand poses problems for network cost efficiencies.

The research group 4DH, for example, aims at tackling this dilemma. The idea is that DH has to undergo a profound technological change in order to be able to keep up with changing requirements, without having high relative losses. This shall be achieved by lower operational temperature levels, high insulation standards and an optimal heat extraction on the consumer's substation. Also the organizational level needs to be adjusted, as electricity systems continue to change, and thus CHP plants need to be operated within electricity smart grids supporting the integration of renewable energy technologies (4DH, n.D., p. 2).

The AGFW (Energy Efficiency Association for Heat, Cooling and CHP) (2012 (a), p. 2) as well as the BKWK (2012) see a very positive signal in the lately amended CHP Act, highlighting the aim of modernizing CHP plants, the support of new DH grids, as well as their expansion, and the construction of thermal storage tanks, which allow a much more flexible operation.

Heat storage tanks, can compensate the fact that electricity and heat demand will often not coincide. Primarily they can absorb the generated heat at times when electricity prices are high (i.e. when there is a low share of RE and CHP plants are in operation), and secondly make sure that heat generating units (both boilers and CHP plants) can operate on a smoothed level, enabling operation at high efficiencies. The latter issue has been dealt with for years; balancing RES on the electricity market, however, is an issue which has not been a matter of priority until lately (IEA, 2011, p. 22).

The example of Denmark shows that a political framework with clear political statements, supporting consumer's comfort and cost savings and not supporting big companies shows that an expansion of DH as well as a successful application of CHP units is possible. Already today the German legislative framework offers a great variety of targets and laws, with most however the consumers resistance to change still needs to be overcome.

11.1.1 GRID EFFICIENCY AND INVESTMENT CALCULATIONS

A performance interpretation and evaluation of existing networks, including a brief economic evaluation of the cost effectiveness of optimization investments is dealt with in answering the second sub-question.

Concerning grid specific efficiency levels, an in depth literature consultation has revealed, that there are certain external, predetermined factors, with which planners need to deal with, like specific heat demand or the building density on the one hand. On the other hand there are many factors which can influence cost efficiency and which can directly be tackled during the planning phase. Here the decision on piping material and size and the stipulation of overall operation temperatures and maximum return flow temperatures need to be mentioned.

Various approaches can be used in order to optimize the grid performance. The discussion of performance optimization goes far beyond the consumer’s behavior and tackles the overall DH system, in optimizing the piping-network and grid components, in finding new loads, as well as opportunities to decrease the overall temperature level.

All options have the common goal to decrease distribution costs, as well as absolute or relative thermal losses, resulting in a competitive heat price. Grid planning also needs to focus on optimal network dimensions in both, pipe diameters, as well as short pipe lengths per house.

In order to find out about the operation efficiency, theoretical losses were determined for various grids; four of which are presented in the report. This has been done on the basis of annual heat sales values as well as annual fuel input. For some grids a great gap between theoretical thermal losses and effective network efficiency became apparent.

According to coinciding statements of various studies, older grids are likely to have increased losses due to decreased insulation qualities of the pipes. With newer networks, however other factors have to have influence on the overall efficiency. At this stage it can only be assumed that it’s the heating unit, which is working at low efficiency in the case of the ZO DH network. According to the applied calculations a total of 20% of the energy of the fuel input is lost, additionally to the determined theoretical loss values caused by the grid. Further investigations need to be carried out in order to determine the causes.

In the case of the Landwasser DH network, increased losses can be assumed to be caused by the aged pipes. A total of 400,000 Euro fuel costs could be saved annually, given a total grid replacement and that all additional losses are solely caused by impaired pipes. A NPV calculation has been conducted, resulting in positive vales when considering an investment timeframe of 5 years and a project period of 20 years, if cost savings can reach ¾ of the determined total value.

11.1.2 SCENARIO ANALYSIS FOR VARYING DEMAND, OPERATIONAL AND GRID COMPONENT PARAMETER

The factors connection ratio, medium temperature and specific heat demand have been identified as being very essential figures. Therefore an evaluation of a fictional network has been undertaken.

20 combinations of these parameters were interpreted and in a next step again evaluated on the basis of two different pipe types and insulation standards. As important information for a DH operator the NPV for investments in a DH network was evaluated, showing whether investments in a DH network can be profitable at varying consumption and operation temperature levels.

Table 16summarizes the results and shows that, when including the scarp value for the grid, which remains after the project period, all investments would be positive; without the inclusion of this value, cost efficiency can only be achieved for the one low heat energy demand scenario of 100% connection ratio with a low temperature network.

As a second evaluation the overall costs for consumers were evaluated, resulting in lower costs for all DH scenarios.

Table 16: Summary of the results of the investment calculations on a DH grid with varying parameter

	1	2	3	4	5	6	7	8	9
Connection ratio	100%	100%	100%	70%	70%	70%	40%	40%	40%
Heat demand	130 kWh/m²								
Line heat density (kWh/m)	3.471	3.471	3.471	2.929	2.929	2.929	2.124	2.124	2.124
Medium temperature	75	60	35	75	60	35	75	60	35
relative loss	6%	5%	3%	7%	5%	3%	9%	8%	4%
NPV excl. scrap value	1.264.023 €	1.425.224 €	1.695.191 €	357.181 €	491.334 €	714.921 €	-525.797 €	-420.595 €	-245.736 €
NPV incl. scrap value	2.975.715 €	3.137.140 €	3.406.883 €	1.777.370 €	1.911.522 €	2.135.109 €	587.916 €	693.118 €	868.201 €

	11	12	13	14	15	16	17	18	19
Connection ratio	100%	100%	100%	70%	70%	70%	40%	40%	40%
Heat demand	60 kWh/m²								
Line heat density (kWh/m)	1.602	1.602	1.602	1.352	1.352	1.352	980	980	980
relative loss	12%	10%	6%	15%	12%	7%	20%	16%	9%
Medium temperature	75	60	35	75	60	35	75	60	35
NPV excl. scrap value	-213.944 €	-53.857 €	212.496 €	-676.607 €	-543.783 €	-322.410 €	-1.112.199 €	-1.008.038 €	-834.915 €
NPV incl. scrap value	1.497.748 €	1.657.835 €	1.924.413 €	743.581 €	876.405 €	1.097.778 €	1.514 €	105.674 €	279.022 €

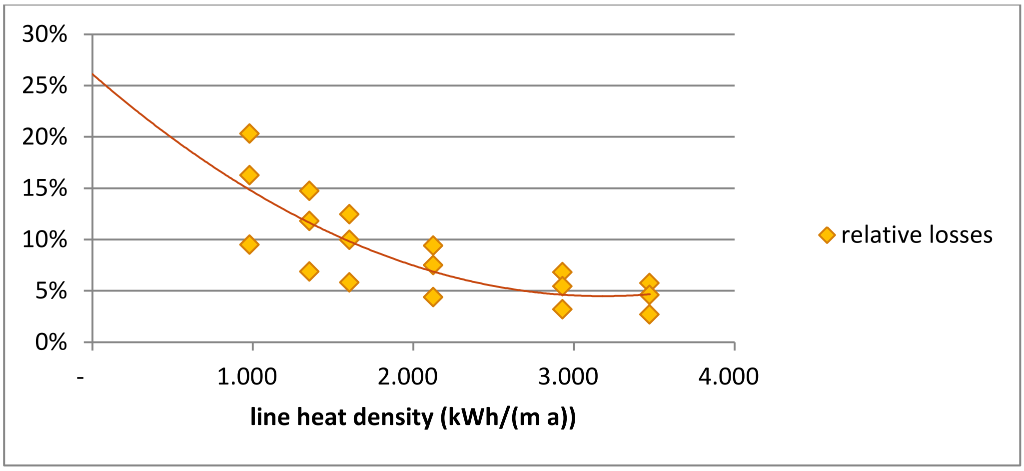

Figure 41: relative losses relative to the line heat density of fictional grids at varying medium temperatures (kWh/(m a))

Considering relative losses, as summarized in Figure 41, the importance of certain efficiency improvement measures gets obvious, especially for low line heat densities. The results might be an explanation for the great variations of minimal line heat densities as mentioned above. While standard grids, for the applied connection ratios of 100, 70 and 40% present relative losses of up to 20%, these values can be lowered to an acceptable 10% if medium temperature is lowered to a value, which can be obtained at a low temperature network. Thus obtained results seem to match with the preliminary results of 4DH or Zinko et al. (2008, p. 9), who present that DH networks can still play a crucial role within the future heat market.

11.1.3 SOCIETAL PREFERENCES

A clear limitation to an expansion of innovative technologies is the customer's fears. The behavioral analysis has revealed that besides technological efficiency, people tend to be very skeptical towards a technology, for which they would have to commit for many years. In Denmark this fear does not seem to be of great importance (at least not any longer). One important reason for this difference has been determined to be the regulation that DH operators are not allowed to strive for profit maximization. While also in Germany, DH operators cannot simply increase prices as they want, this clear legislative regulation seems to make a difference.

11.2 FINAL CONCLUSION

As can be seen by the performed calculations, profitability very much depends on the assumptions which underlie the analyzed system.

For the results being rather fragile, all components would need to be included and a profound analysis for each single buildings heat demand needs to be carried out, in case of a planning of a real grid. Also investment costs would need to be obtained through offers of the specific companies. For the purpose of the study however this calculation depth has been considered to be sufficient as the primary aim of the analysis has been to show effects of varying parameter on the profitability of a potential investment.

One general, simplified conclusion can be drawn from the results: The lower the line heat density the more important the optimization measures. Already today also for higher line heat demands, however there is considerable potential for performance optimization. In the future these measures will be more critical for overall profitability.

It has to be pointed out, that possibly current cost inefficiency does not mean that this will be the final result. While a central unit can react quickly towards price and resource variations, individual installations will be dependent on one single resource throughout their lifetime. This advantage should not be underestimated.

Certainly data collection and metering has to be improved. With intelligent meters it is possible to allow for new billing methods, persuading the customers to improve the heat extraction at their substation. It will also benefit the consumer, as he will be better informed about his performance. Besides more detailed data recording would also allow better interpretations of the arising pumping costs which are assumed to be very high, if customers do not comply with the contractual temperatures.

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Apendix-B

Internal Factors	STRENGTHS - Positive image /reputation also due to mother company's policy → Local prominence - Offering efficient, environmentally friendly services - Easy and reliable technology for consumers - Competitive and stable prices – low O&M costs - Fuel flexibility - Security of supply - Expierenced and innovative employees - Many well working network examples	WEAKNESSES - Inflexibility in pricing and billing policy (due to mother company's regulations) - Due to ownership structure, hardly any control of consumer's substations → Operational challenges - High investment costs / capital intensive technology - Serious interference in municipal infrastructure (if not built up from scratch)
External Factors **(PESTLE)**	OPPORTUNITIES - Increasing legislative regulations → Connection dictate possible → Funding possibilities → Demand for smart infrastructure → More decentral electricity production (CHP) → Climate Change mitigation → Increasing shares in RES → Increasing efficiency standards - Increasing awareness for energy efficiency and environmental threats - Rising fossil fuel prices - Utilization of waste heat - Increasing living space - Innovations (e.g. low temperature DH) - Remote reading enables different tariffs (management of demand peaks or control of consumer's substations)	THREATS - Increasing legislative regulations (Sometimes: 'You must not touch the voter's life, but emissions and energy consumption must be reduced' **Es ist eine ungültige Quelle angegeben.**) → Quickly changing regulations concerning emissions, RES and CHP → Stricter DMS regulations = lower heat demands → Comparably low RD&D investments - Conservative consumers (strong habits and low risk taking) - Competitive heating forms - Growing competition of /conflict of interest with RES usage

Apendix-C

Tabelle 1: Heat conductivity for different insulation standards and varying nominal diameters [W/m K]

	Single Pipe			Twin Pipe	
DN	Standard	1 x insulated	2 x insulated	Standard	1 x insulated
25	0,3304	0,2758	0,2498	0,2268	0,1990
32	0,3376	0,2996	0,2724	0,2469	0,2172
40	0,3870	0,3376	0,3036	0,2909	0,2469
50	0,4310	0,3770	0,3288	0,2848	0,2452
65	0,5054	0,4222	0,3688	0,3352	0,2826
80	0,5212	0,4422	0,3940	0,3774	0,3031
100	0,5524	0,4644	0,4074	0,3808	0,3052
125	0,6358	0,5336	0,4550	0,3539	0,2912
150	0,7492	0,6028	0,5024	0,4264	0,3363
200	0,8150	0,6406	0,5274	0,4833	0,3557
250	0,7938	0,6282	0,5298		
300	0,9114	0,7180	0,5844		
350	0,8906	0,6940	0,5640		
400	0,9484	0,7212	0,6412		
450	0,9562	0,8206	0,7236		
500	1,0944	0,9284	0,7074		

Apendix-D

Network Statistics		Landwasser	Stetten Süd	Vauban	ZO
General Characteristics	Supplied area (km2)	0,54	0,23	0,37	0,03
	Connected houses (HASP)	65	112	169	13
	Indirectly connected houses	-	-	145	5
	Grid length (m)	7.626	5.991	6.714	599
	Fuel input (kWh)	49.025.545	7.014.403	18.548.331	3.238.733
Energy demand values	Space heat demand (kWh)	10.599.238	2.099.478	4.341.329	728.649
	Hot water demand (kWh)	17.920.771	2.120.184	7.090.943	705.710
	Total heat demand (kWh/m²)			68,8	105,2
Energy demand values	Space heat demand (kWh/m²)			26,1	53,4
	Hot water demand (kWh/m²)			42,7	51,7
	Thermal losses (kWh/m²)			7,3	8,0
	Line heat density (kWh/m a)	3.740	704	1.703	2.395
	Sales (including. electricity)	35.145.619	5.203.235	14.984.476	2.179.227
	Heat density (kWh/km²)	52.814.831	18.106.640	30.661.853	47.811.967

Status Quo		Landwasser	Stetten Süd	Vauban	ZO
Low temperature grid (60/30 & 40/20)	Thermal loss (%)	3,3%	10,8%	5,6%	3,8%
TAB - 15°C	Thermal loss (%)	5,0%	15,7%	8,1%	6,0%
RL TAB	Thermal loss (%)	5,9%	18,2%	9,5%	7,1%
TAB + 10°C	Thermal loss (%)	6,5%	19,7%	10,5%	7,7%
TAB + 20°C	Thermal loss (%)	7,1%	21,2%	11,4%	8,4%
Low temperature grid (60/30 & 40/20)	Thermal loss / Tm	129,4	84,9	101,1	95,3
TAB - 15°C	Thermal loss / Tm	196,1	131,7	150,1	154,2
RL TAB	Thermal loss / Tm	233,8	156,4	179,5	181,9
TAB + 10°C	Thermal loss / Tm	258,9	172,8	199,1	200,4
TAB + 20°C	Thermal loss / Tm	284,0	189,3	218,7	218,9
Low temperature grid (60/30 & 40/20)	Missing energy	15,9%	5,9%	4,7%	23,4%
TAB - 15°C	Missing energy	14,7%	1,2%	2,7%	22,2%
RL TAB	Missing energy	14,0%	-1,3%	1,5%	21,6%
TAB + 10°C	Missing energy	13,6%	-3,0%	0,6%	21,2%
TAB + 20°C	Missing energy	13,1%	-4,6%	-0,2%	20,8%
Low temperature grid (60/30 & 40/20)	Volume flow (10m³)	163.994	22.872	65.383	7.670
TAB - 15°C	Volume flow (10m³)	45.778	7.639	18.999	2.444
RL TAB	Volume flow (10m³)	64.482	11.315	27.005	3.496
TAB + 10°C	Volume flow (10m³)	89.591	16.911	37.850	4.926
TAB + 20°C	Volume flow (10m³)	153.185	37.471	65.383	8.523

Low temperature grid (60/30 & 40/20)	Costs (€)	2.066.824	186.241	494.948	69.403
TAB - 15°C	Costs (€)	2.096.384	195.537	505.529	70.521
RL TAB	Costs (€)	2.113.068	200.443	511.878	71.047
TAB + 10°C	Costs (€)	2.124.191	203.714	516.111	71.398
TAB + 20°C	Costs (€)	2.135.314	206.984	520.343	71.749
Low temperature grid (60/30 & 40/20)	Costs (€) - missing energy	390.422	11.626	24.481	21.217
TAB - 15°C	Costs (€) - missing energy	360.862	2.330	13.899	20.099
RL TAB	Costs (€) - missing energy	344.178	-2.575	7.550	19.572
TAB + 10°C	Costs (€) - missing energy	333.055	-5.846	3.318	19.221
TAB + 20°C	Costs (€) - missing energy	321.932	-9.116	-915	18.870
Low temperature grid (60/30 & 40/20)	Emissions (total) (kg)	6.156.258	1.659.438	4.046.589	622.590
TAB - 15°C	Emissions (total) (kg)	6.244.305	1.742.266	4.133.101	632.620
RL TAB	Emissions (total) (kg)	6.294.001	1.785.976	4.185.008	637.344
TAB + 10°C	Emissions (total) (kg)	6.327.132	1.815.116	4.219.613	640.493
TAB + 20°C	Emissions (total) (kg)	6.360.263	1.844.256	4.254.218	643.642
Low temperature grid (60/30 & 40/20)	Emissions (compared to TAB)	-2,2%	-7,1%	-3,3%	-2,3%
TAB - 15°C	Emissions (compared to TAB)	-0,8%	-2,4%	-1,2%	-0,7%
RL TAB	Emissions (compared to TAB)	0,0%	0,0%	0,0%	0,0%
TAB + 10°C	Emissions (compared to TAB)	0,5%	1,6%	0,8%	0,5%
TAB + 20°C	Emissions (compared to TAB)	1,1%	3,3%	1,7%	1,0%

Demand reduction (50%)		Landwasser	Stetten Süd	Vauban	ZO
Low temperature grid (60/30 & 40/20)	Thermal loss (%)	4,1%	13,8%	6,8%	5,1%
TAB - 15°C	Thermal loss (%)	6,1%	19,9%	9,8%	7,9%
RL TAB	Thermal loss (%)	7,1%	22,8%	11,5%	9,2%
TAB + 10°C	Thermal loss (%)	7,8%	24,6%	12,6%	10,1%
TAB + 20°C	Thermal loss (%)	8,5%	26,3%	13,7%	10,9%
Low temperature grid (60/30 & 40/20)	Thermal loss / Tm	129,4	84,9	101,1	95,3
TAB - 15°C	Thermal loss / Tm	196,1	131,7	150,1	154,2
RL TAB	Thermal loss / Tm	233,8	156,4	179,5	181,9
TAB + 10°C	Thermal loss / Tm	258,9	172,8	199,1	200,4
TAB + 20°C	Thermal loss / Tm	284,0	189,3	218,7	218,9
Low temperature grid (60/30 & 40/20)	Volume flow ($10m^3$)	142.194	18.555	56.507	6.206
TAB - 15°C	Volume flow ($10m^3$)	38.246	5.892	15.714	1.856
RL TAB	Volume flow ($10m^3$)	54.406	8.838	22.524	2.676
TAB + 10°C	Volume flow ($10m^3$)	76.534	13.461	31.913	3.810
TAB + 20°C	Volume flow ($10m^3$)	134.407	31.629	56.507	6.761
Low temperature grid (60/30 & 40/20)	Costs (€)	1.582.830	136.717	372.415	46.800
TAB - 15°C	Costs (€)	1.612.390	146.013	382.996	47.918
RL TAB	Costs (€)	1.629.074	150.919	389.345	48.444
TAB + 10°C	Costs (€)	1.640.197	154.189	393.578	48.795

TAB + 20°C	**Costs (€)**	1.651.320	157.460	397.810	49.147
Low temperature grid (60/30 & 40/20)	**Costs (compared to status quo)**	-23,4%	-26,6%	-24,8%	-32,6%
TAB - 15°C	**Costs (compared to status quo)**	-23,1%	-25,3%	-24,2%	-32,1%
RL TAB	**Costs (compared to status quo)**	-22,9%	-24,7%	-23,9%	-31,8%
TAB + 10°C	**Costs (compared to status quo)**	-22,8%	-24,3%	-23,7%	-31,7%
TAB + 20°C	**Costs (compared to status quo)**	-22,7%	-23,9%	-23,5%	-31,5%
Low temperature grid (60/30 & 40/20)	**Emissions (total) (kg)**	4.714.628	1.218.169	3.044.784	419.826
TAB - 15°C	**Emissions (total) (kg)**	4.802.676	1.300.997	3.131.296	429.856
RL TAB	**Emissions (total) (kg)**	4.852.372	1.344.707	3.183.204	434.580
TAB + 10°C	**Emissions (total) (kg)**	4.885.503	1.373.848	3.217.808	437.729
TAB + 20°C	**Emissions (total) (kg)**	4.918.634	1.402.988	3.252.413	440.879

Grid substitution					
Low temperature grid (60/30 & 40/20)	**Thermal loss (%)**	1,9%	7,5%	3,4%	2,3%
TAB - 15°C	**Thermal loss (%)**	2,9%	11,2%	4,9%	3,7%
RL TAB	**Thermal loss (%)**	3,4%	13,0%	5,8%	4,3%
TAB + 10°C	**Thermal loss (%)**	3,8%	14,2%	6,4%	4,7%
TAB + 20°C	**Thermal loss (%)**	4,1%	15,3%	7,0%	5,1%
Low temperature grid (60/30 & 40/20)	**Vergleich Thermal loss ohne Ren. (%)**	-43,4%	-32,7%	-41,6%	-40,7%
TAB - 15°C	**Vergleich Thermal loss ohne Ren. (%)**	-43,4%	-32,7%	-41,6%	-40,7%
RL TAB	**Vergleich Thermal loss ohne Ren. (%)**	-43,4%	-32,7%	-41,6%	-40,7%
TAB + 10°C	**Vergleich Thermal loss ohne Ren. (%)**	-43,4%	-32,7%	-41,6%	-40,7%
TAB + 20°C	**Vergleich Thermal loss ohne Ren. (%)**	-43,4%	-32,7%	-41,6%	-40,7%
Low temperature grid (60/30 & 40/20)	**Costs (€)**	2.045.345	181.551	487.037	68.753
TAB - 15°C	**Costs (€)**	2.063.837	188.262	493.783	69.470
RL TAB	**Costs (€)**	2.074.274	191.804	497.831	69.807
TAB + 10°C	**Costs (€)**	2.081.232	194.165	500.530	70.033
TAB + 20°C	**Costs (€)**	2.088.191	196.526	503.229	70.258
Low temperature grid (60/30 & 40/20)	**Costs (compared to status quo)**	-1,0%	-2,5%	-1,6%	-0,9%
TAB - 15°C	**Costs (compared to status quo)**	-1,6%	-3,7%	-2,3%	-1,5%
RL TAB	**Costs (compared to status quo)**	-1,8%	-4,3%	-2,7%	-1,7%
TAB + 10°C	**Costs (compared to status quo)**	-2,0%	-4,7%	-3,0%	-1,9%
TAB + 20°C	**Costs (compared to status quo)**	-2,2%	-5,1%	-3,3%	-2,1%