The potential of Solar District Heating in Germany's Bioenergy-Villages

– Assessment of the techno-economic potential, biomass resources and socio-organisational barriers

Master Thesis
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Submitted by

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Abstract:
By conducting a three-fold analysis this master-thesis tackles the problem on how the solar thermal fraction of Solar District Heating (SDH) technology can potentially contribute to the transition of Germany's "*Bioenergiedörfer*" (BED) district heating systems. First, the techno-economic potential is analyzed resulting in 74 suited villages with a demand side potential of about 240,000 m^2 worth the capital price of 121 Million EUR. Second, two groups of BED were found comprising a demand side potential due to technical specification. Second, analyzing the BED's adjacent biomass residue potentials in a circumstance of 50 km, which should influence the planning process of RES systems in rural areas. Third, it studies the existing technological, organisational, decision-making and economic barriers that hinder the SDH potential of the BED from being utilized and further unfolds potential approaches how specific barriers could be overcome.

By signing this document, I declare that this report was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text. The content of this report is freely available, but publication (with reference) may only be pursued due to agreement with the author.

Jonas Immanuel Ott

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Over and above, I want to thank my colleagues from Aalborg CSP. Jes Donneborg, for proposing the topic of Solar District Heating and *Bioenergiedörfer* and making this collaborative master-thesis possible; Lasse Kristensen, for providing me with information on SDH system base prices as well as Per Aasted, for his elaborate technical explanations. Further, I would like to thank my supervisor Karl Sperling from *Aalborg Universitet* for all the meetings with prolific feedback and for instantly picking up my request for supervision. Additionally, Anna Lea Eggart (student of "Cities and Sustainability") for her support in initially mapping the villages and resources in Q-GIS, as well as Niels Bach-Sørensen for implementing the biomass spacial analysis with PostGIS. Moreover, both my brother Lukas for proof-reading and annotations - as well as Christian Hurtado, in particular for correcting my English language from the distant Toronto. Furthermore, I want to thank all seven interviewees and experts on Bioenergy-Villages and Solar District Heating who contributed with interest and disclosed information in interviews, via (video-)calls due to COVID-19, on current barriers and further for final proof-reading my notes.

Preface & Disclaimer

This Master thesis was conducted between February, 1^{st} and June 4^{th} 2020 as the final project of the Master of Science programme *Urban, Energy and Environmental Planning* in the specialisation *Sustainable Energy Planning & Management* at Aalborg University.
The subject of the thesis was selected due to the preceding proposal of Jes Donneborg from *Aalborg CSP* in order to better understand the options and potentials that German Bioenergy-Villages provide for an implementation of Solar District Heating.
Moreover, the idea behind the Bioenergy-Village movement greatly matched my particular interest and conviction that the energy transition underway should be based on a two-sided approach. On one side, it should make use of simple, harmless and convivial as renewable energy technologies. On the other side be organized as a bottum-up citizen energy project. To underscore this importance I added a section to my research design explaining my fundamental values by discussing relevant conceptual frameworks and relating these to the Bioenergy-Villages approach in the backdrop of 21^{st} century' problems.
Moreover, I would like to contextualize how also my work and eventually research design was impacted by the COVID-19 pandemic coming about contemporaneously. On March 13^{th}, 2020 alongside with other measures the Danish government decided as part of their containment strategy to close down the country's academic and educational institutions and also (most) Danish companies had to change to work from home. Regarding the process of my Master thesis the main influence of COVID-19 that I could not partially work from Aalborg CSP thus missing out input and feedback from my colleagues - which was to a great extent the reason why I decided to conduct the research on my Master thesis alone and not as a group work. My original idea of the research design was to, first, generally conduct a meta-analysis of the BED in order to then focus on two or three subjects with a high potential in order to scrutinizing the specific possibility of solar district heating in these villages by the means of an energy system model. However, the impact of COVID-19 regulations prevented me from conducting in situ interviews focusing on respective BED with a high potential. Therefore, I had to change my research design focusing on studying the circumventing barriers that hinder Bioenergy-Villages from adopting Solar District Heating a part of a solution to their individual energy transitions. Further, delimitations as well as limitations will be explained course of this report.

Aalborg, 4^{th} June 2020

Executive Summary

The problem addressed of my master-thesis is Germany's heating transition. In particular, the techno-economical potential and barriers on a social and organisational level hindering the use of solar thermal systems' (STS) potential being employed in district heating (DH) sector of Germany's Bioenergy-Villages (BED - "Bioenergiedörfer"). Also Germany's heating sector, that today has a low share of DH and STS, requires to transition its supply towards renewable energy sources (RES) - and thus likely also Solar District Heating (SDH). It is recommended for Germany and particularly her rural rural areas to raise the solar thermal fraction due to environmental and economical considerations. Germany's BED movement represents the rural energy transition movement and was selected as a research subject. The BED district heating systems are fueled on domestic limited biomass (BM) and biogas resources and also often organize their RES technology differently in terms of ownership and decision-making, compared with the old fossil-fueled centralized energy system. The problem on how particularly the solar thermal fraction of Bioenergy-Villages can be raised was tackled by the conduction of a three-fold analysis based on a methodological approach, comprising also own methods of (M1) literature review, (M2.1) Multi-Criteria-Analysis (MCA), (M2.2) techno-economical demand side calculation, (M3) GIS-based biomass potential analysis and (M4) semi-structured interviews on social-organisational barriers. The approach resulted in two groups of BED comprising a high potential for SDH due to technological supply side specifications and a total of 74 villages fulfilling the minimum heat demand criteria representing a potential of about 238,000 m^2 equivalent to a base capital price of 121 M €. Three types of BM residue energy potentials in a circumference of 50 km of each BED were conducted. The BED, particularly ones with low local BM are advised to bear the indicative criterion of a locally limited BM resources in mind when planning their individual RES systems. The method's calculation can be improved and should flow into the MCA and GIS-based energy planning tools. At this stage, an in-depth analysis of BED systems comprising a high potentials and also low BM potentials is recommendable. As SDH technology found being mature for implementation, the limiting barriers lie within the BED: e.g. SDH being widely unknown in Germany, what can be overcome with excursions. For implementation of RES/SDH projects the support of a maker in each BED is required. There is a tendency of the BED's location, rather than its legal form being decisive for BED to pick a SDH system. Funding-programs of 2020 seem to be suitable, but should have an upper and lower limit. Two potential policies could be derived: (i) "funding corridor" and (ii) assigning municipalities to keep free land areas.

Contents

Glossary

BED - Bioenergy-Village ("*Bioenergiedorf*")
BG - Biogas
BM - Biomass
BMP - Biomass Potential
BW - Baden-Württemberg
BY - Bavaria
CHP - Combined Heat and Power
CSP - concentrating solar power
CR - Connection Rate
EEG - Renewable Energy Source Act ("*Erneuerbare Energien Gesetz*")
FNR - German authority for re-growing resources ("*Fachagentur für nachwachsende Rohstoffe*")
GIS - Geographic Information System
GoT - GREENoneTECH (solar collector supplier)
HD - heat demand
IBEG - Institute for Bioenergy-Villages ("*Institut für Bioenergiedörfer*")
MCA - Multi-Criteria-Analysis
MV - Mecklenburg-Vorpommern
NI - Niedersachsen
pBED - planned Bioenergy-Villages (not acknowledged by FNR)
REP - residue energy potential
RES - renewable energy sources
SH - Schleswig Holstein
SDH - Solar District Heating
STC - Solar Thermal Collector
STS - Solar Thermal System
SR - Supply Rate
TES - Thermal Energy Storage

Abbreviations
k/M/G/T/P- kilo/Mega/Giga/Terra/Peta
J - Joule
Wh$_{(th/el)}$ - Watt hours (thermal/electric)
W$_{(th/el)}$ - Watt (thermal/electric)

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1 | Introduction

An energy transition world-wide is required as a main means to avoiding tremendous damages due to our own species' activity on our and other species' habitat - Planet Earth. In order to fight the climate change crisis and to dampen Holocene extinction, also referred to as the sixth mass extinction that is under way today, it is required to design completely new energy systems based on renewable energy sources (RES). The great majority of scientist scholars are clearly warning humanity of the foreseeable threat and demand changes right now in order to avoid a total climate and species extinction breakdown. In the opinion of many scholars and scientists world-wide, the energy sector is seen as the core of any existent modern societies, thus also being the core that requires a re-design - on a technological (RES based), but also on a socio-organisational in terms of establishing a citizen-run democratic energy system. The case of Germany is regarded "as an international showcase for the transition of a large industrialized economy to a low-carbon energy system" [Rommel et al., 2018, p.1] coming from an energy system totally based on fossil fuels and nuclear energy and shifting slowly towards a RES system. This and no less is what the Paris Pledge and the Climate Agreement from December, 2015 are about: the decarbonization of the world's economy and keeping temperature rise below 2C. [COP21]

1.1 Germany's *Energiewende* and citizen participation

Germany's energy transition ("*Energiewende*") is aiming at a long-term structural change of the energy system, not just on a mere technological level, but also on an organisational level. In 2013, 47% (34 Giga-Watt (GW) out of 73 GW) of Germany's installed energy conversion or generating capacity to harvest energy from RES was owned by the citizens - thus being almost four times as high as the share (9 GW) of the big utility companies in RES capacities in 2013.[trend:research/Leuphana and Lüneburg, 2013] From this context emerged various new business and participation models ranging from traditional market-centered forms to new forms embracing citizen participation summarized under the term citizen energy ("*Bürgerenergie*").

1.1.1 Transition of Germany's heating sector

The energy transition, in Germany as everywhere else, is required to take place in three different sectors of energy usage that are namely (i) electricity, (ii) mobility and (iii) heating and cooling. The latter has received surprisingly little attention so far - though the energy consumption of heating and cooling represents almost 50% of the European Union's primary energy usage [Rämä and Mohammadi, 2017]. Thermal energy generation (which encompasses both heating and cooling) is a significant source of carbon dioxide emissions due to it primarily being reliant on the burning of fossil fuels. Generally, district heating (DH) is not commonly used in Germany, and when it is used, RES does not make up a large share of the consumed energy. In 2015, in Germany the total RES in heating share in DH was at 9% [Schulz, 2016, Paardekooper et al., 2018] - whereas in Denmark it was at 48% [Schulz, 2016]. Key for the heating transition is the development of the so-called fourth generation of district heating networks. This implies long-term infrastructure planning with new features such as low temperature heat distribution, improved utilisation of excess energy of industries and, most importantly RES based technology. [Lund et al., 2014] So far, the base load in traditional DH systems is covered by combined heat and power (CHP) plants that are run on "natural gas" (henceforth "fossil gas"). To limit the carbon emissions of a CHP plant, the fossil gas must be replaced by a RES. The different RES' characteristics lead to more complex DH systems due to their the local variation and fluctuations in energy generation due to weather dependency. As a consequence to this, thermal heat storage (TES) and smart control systems need to be taken into consideration in order to manage and match heat supply and demand. [Rämä and Mohammadi, 2017, Carpaneto et al., 2015] This is why technologies such as Solar Thermal Systems (STS) , CHP and geothermal have been present in the public policy discussion, since they are promising to reduce CO_2 drastically. In 2016, this discussion peaked in a "heating and cooling strategy"[European Comission, 2016] by the European Union that is viewed as an approach to address the challenges addressed by the COP21 in Paris 2015 .

1.1.2 Biomass and solar thermal in Germany heating

The German authority for re-growing biomass resources FNR ("*Fachagentur für nachwachsende Rohstoffe*") estimates that Germany's domestic biomass (BM) will have the potential to cover 26% (or 1,819 Peta Joule) of the country‘s overall energy demand by 2050, assuming all three energy sectors experience a drastic energy reduction [Fachagentur für nachwachsende Rohstoffe, 2016]. Even though the relative efficiency - also referred to as 'energy harvesting potential (kWh/m^2*a)' - of biomass is determined to be approximately 50 times lower than that of solar collectors [Sørensen et al., 2012], solar thermal collectors are hardly used in Germany. In Germany, of the different RES used for heating water, solar thermal energy represented 4.8% in 2019 while BM account for approximately two-thirds. [Umweltbundesamt, 2020]. A study on Germany's heating transition concludes that reaching 14% (equal to 100 TWh$_{th}$) of role-out of solar thermal is a feasible scenario for Germany within the next 25 to 35 years [Kunz and Kirrmann, 2016, p. 30]. Also taking area-intensive electricity generation by solar photovoltaics into consideration, open areas and roof tops will not be the limiting factor for the solar thermal heating fraction in Germany to reach the 14% goals [Kunz and Kirrmann, 2016, p. 24]. Solar collectors have been gaining more attention during the past years, being viewed as a key technology for potentially providing a base-supply of energy[Lund et al., 2014], mainly due to two reasons: (I) a decrease in the investment costs and (II) an increase of the price of conventional fossil fuels.[Rämä and Mohammadi, 2017] Operating solar collectors on a larger scale and combining it with DH is called Solar District Heating (SDH). Germany's adjacent country of Denmark has a lower irradiance potential than Germany, but 80% of Europe's installed capacity of SDH over the past 15 years is located there. For instance, there is SDH in Marstal, Denmark, where 55% of the heat demand is supplied by 3,300 m^2 [Co2mmunity, 2019]. Today, the fact that dozens of SDH facilities are operational and the existence of detailed guidelines show that SDH can be operated feasibly in central Europe. [Sørensen et al., 2012] SDH can be operated in conjunction with other renewable energies such as heat pumps and, of particular relevance to this thesis, biomass. Germany's Agency for Renewable Energies ("*Agentur für Erneuerbare Energien*") considers the combination of biomass-fuelled boilers with solar thermal collectors (STC) in Germany's DH network to be a promising niche, offering immense development potential in the country's heat transition towards RES. [Alexander Knebel and Vohrer, 2016] Moreover, SDH in combination with large-scale thermal storage can theoretically provide 90 % of the heating demand throughout Europe and reduce the total environmental impact by 82.1 % (Berlin) compared to fossil gas. [Tulus et al., 2019]

1.2 Bioenergy-Villages as research subject

Bioenergy-Villages (BED - "*Bioenergiedörfer*") in Germany were chosen as research subject for four reasons:

1. BED or also planned BEDs have district heating (DH) systems installed which is considered a prerequisite for the use of large-scale solar thermal systems (STS), such as SDH, to supply heat.
2. BED are expected to adapt well to climate change because they apply an RES-focused technological approach by fuelling their DH systems for the most part with biomass and biogas.
3. BED comprise a citizen energy approach and are thus potentially pioneering in Germany's *Energiewende*, which happens not only on a RES technological level, but also on a socio-organisational level as bottom-up energy-initiatives [Akizu et al., 2018]. I am personally highly interested in a combination out convivial bottom-up energy transition towards "renewable energy villages". [Jenssen et al., 2014, p. 7].
4. I have been employed as a student job at *Aalborg CSP*, the company is interested in learning about the opportunities, but also potential hindrances of Germany's SDH sector.

2 | Problem Formulation

The problem being addressed by this master thesis is the heating transition in Germany, thereby it focuses on Bioenergy-Villages (BED "*Bioenergiedörfer*") as a research subject. This report seeks to answer questions on the techno-economic potential and socio-organisational barriers that curb the potential utilisation of large-scale solar thermal as a renewable energy source (RES) in the district heating (DH) systems of Germany's Bioenergy-Villages (BED).

In 2019, solar thermal represented 4.9% of Germany's heating energy supply and it played a minor role in fuelling district heating (DH) systems in Germany [Umweltbundesamt, 2020]. It is realistic to increase the solar share to 14% in order to transition towards a more decentralized and renewable energy-based system. [Kunz and Kirrmann, 2016, p. 23] Further, some scholars argue that what is required to transform the heating sector is first, a smart-grid and second, a mix of renewable energy[Lund et al., 2014]. The share of district heating in Germany's residential sectors is estimated to be optimal at covering approximately half of the residential heating demand (49%) [Paardekooper et al., 2018]. Solar thermal in DH is not yet broadly used in Germany's rural context of BED, however, presenting a methodological hurdle of sorts. GIS-based projects such as "Heat Map Europe" that seek to identify strategic heat synergy regions [Persson et al., 2014], and further to merge the European heat demand and supply sides[Möller et al., 2018], pose as potential solutions for overcoming this hurdle. However, at the time of writing this thesis, there was no tool available that directly calculates the demand and potential for SDH of each German villages and also indicates the capital cost.

Biomass limitation and solar thermal potential of Bioenergy-Villages In 2020, most of Germany's 159 BED have decentralized DH systems whose supplies are at least 50% bio-energy.[Fachagentur für nachwachsende Rohstoffe, b, 05/2020] In most cases, combined-heat-and-power (CHP) facilities generate electricity and heat that is fed into the local DH systems. The rising demand for biomass paired with an increasing number of BED has led to a demand in locally produced bio-energy fuels that is growing faster than the local supply[Berberich and Pauschinger, 2018]. Further, land-use conflicts with the animal-based aliments, dairy and meat production industries is leading to serious conflicts and, in some cases, limitations of German domestic BM usage [Umweltbundesamt, 2019]. This happens against the backdrop of demand for biomass projected to increase from 360 PJ in 2015 to around 640 PJ in 2050.[Kraan, 2015] As a consequence to the foreseeable biomass limitations, some researchers demand that "the concept of bioenergy villages should to a greater extent be opened up to other renewable sources turning it into a concept of renewable energy villages." [Jenssen et al., 2014, p. 7]. To enhance this transition, further research is needed. Generally, a certain potential is subscribed to the solar thermal technology. In order to plan for the optimal mix of RES, the potential access to local domestic and sustainable RES such as wind, solar and geothermal must be gauged. The potential limitation of BM is important to understand for BED to make adequate decisions on which alternative RES should be integrated. No suiting method could be find to analyze the BM potential of Germany villages, so that own method was developed. Some scholars describe BED as socio-technological systems, of which "the dynamics of community renewable energy has not been well understood until now".[Von Bock Und Polach et al., 2015, p.1] A survey tried to understand acceptance of larger solar thermal systems in German rural areas [Geiger, 2019]. It found that existing barriers inside the BED villages such as decision-making structures and general techno-economic framework conditions (e.g. funding/taxes) do hypothetically influence the BED's decision to augment their energy supply by using alternative RES. Thus understanding and overcoming these barriers in terms of organisational structures and characteristics can be considered key to unleashing the socio-organisational and the techno-economic potential for SDH. This would further facilitate to transition BED's sustainable energy concepts towards one of renewable energy villages.

2.1 Methodology and research questions

This thesis seeks to conduct a three-fold analysis of different aspects of potential for SDH in BED. First, the analysis of the techno-economic potential from the supply and demand sides is one of the investigative focuses of this thesis. Here, there was no methodological framework, program or tool given in order to estimate the potential. Second, an assessment aimed at understanding how local biomass residue potential as main renewable energy resource of the BED, is diverging and limited in the circumference of the villages. Third, the development of a deeper understanding of the socio-organisational barriers of the "competing" RES technologies to enable a 100% RES-based heating system. To conduct these analyses, there was no direct tool or methodology given to estimate the techno-economic potential, to analyse the biomass potential of the adjacent areas, and third to understand the barriers. For the last analysis, expert interviews were used. On these grounds, the whole methodological approach was developed for the three-fold analysis, which is presented in the next Chapter 3 on the Research Design and in each subsequent Chapter. The analysed problems flow into the following over-arching research question that consists of four sub-research questions:

Main **Research Question**:

- How can the use of Solar District Heating as a primary alternative renewable energy source contribute to the transformation of Germany's Bioenergy-Villages' (district) heating sector, particularly with respect to the techno-economic potential and their socio-organisational hindrances?

This main RQ is split up into the four enumerated sub-research questions tackled in the next four chapters.

1. What is the status quo and underlying frameworks of Germany's heating sector, it's supply by different renewable energy sources, particularly biomass and solar thermal as well as the the status of Bioenergy-Villages today? (Chapter 4)

2. How can the techno-economic potential for Solar District Heating in Bioenergy-Villages be assessed in terms of energy demand, area and price and what groups of Bioenergy-Village show to have a high potential for the application of alternative heat supply technologies? (Chapter 5)

3. To what extent can other external technological renewable resource potentials be considered and how can their influence on the application of the usage of solar thermal systems in the Bioenergy-Villages' heating sector be quantified? (Chapter 6)

4. To what degree do socio-organisational and techno-economic barriers hinder the implementation of alternative RES technology to supply Bioenergy-Villages' district heating and what are potential approaches to overcome them? (Chapter 7),

2.2 Delimitations

In this report, I focus on the (district) heating sector of BED as a residential area. Industrial or highly dense urban areas as well as other small DH systems outside BED will not be subject of this thesis. Though its main focus is solar thermal energy supply, it will bear the issue of sector coupling in mind, though sector coupling itself is not the focus. This work does not intend to analyse the DH systems themselves and how solar thermal system can be technically integrated, nor does it focus on heat saving on the demand side: e.g. the building or construction side requirements such as energy savings through insulation. Further, it does not seek to analyze the specific land (area) requirements of solar thermal for the different BED and it also does not aim to assess the environmental impacts of a renewable energy-powered district heating system.

3 | Research Design & Methodology

This chapter aims to present the research design (section 3.1) and introduce the methods that are utilized in combination to answer the research questions of this report. Further, it presents, in section 3.2, an introspective into my personal underlying philosophical framework and socio-technological belief. I do so partly to explain concepts, but also to be transparent in presenting what has informed my research and how conducting this master's research on Bioenergy-Villages (BED) coincides with my philosophical foundation, that I try to unfold by discussing relevant conceptual frameworks.

3.1 Introduction and overview on Research Design and Methodology

In order to tackle the problem and research questions depicted in the previous chapter 2, the following Research Design and methodology were developed. The methods are introduced in the subsections below and are applied in-depth in the various chapters of the analyses. Below, I explain the Research Design presented below in Figure 3.1 by going from the top-left to the bottom-right. The first answer to the first sub-research question (1.) aims to provide both conceptual and contextualized knowledge. This is presented in the theoretical framework chapter 4 by elaborating the understanding of Germany's Bioenergy-Villages ('Bioenergiedörfer' - BED) and the problematic situation of the heating sector lacking renewable energy source (RES) supply. This sub-question also analyzes the status quo of solar thermal systems (STS) combined with district heating (DH). The same chapter presents the restrictions of the limited bioenergy resources in Germany, all of which is based on method **(M1) literature review**. In chapter 5, the sub-research questions (2.) on the techno-economic potential is addressed by using a **(M2.1) Multi-Criteria-Analysis (MCA)**. This method is utilized in a subsequent linked analysis of BED's two-fold **techno-economic potential (M2.2)** to estimate the potential from the demand and supply sides. The created data-sheet and basis of the MCA is for it to act as a tool to perform an overall analysis of the BED to find 1. concrete BED with a high supply side potential (1., red text in Figure 3.1) and BEDS that can serve as Good Practices (2, purple text). The MCA also outputs information on the distribution of legal forms and regions of BED (3., blue text), which was used later as input in the socio-organisational potential analysis (M4).

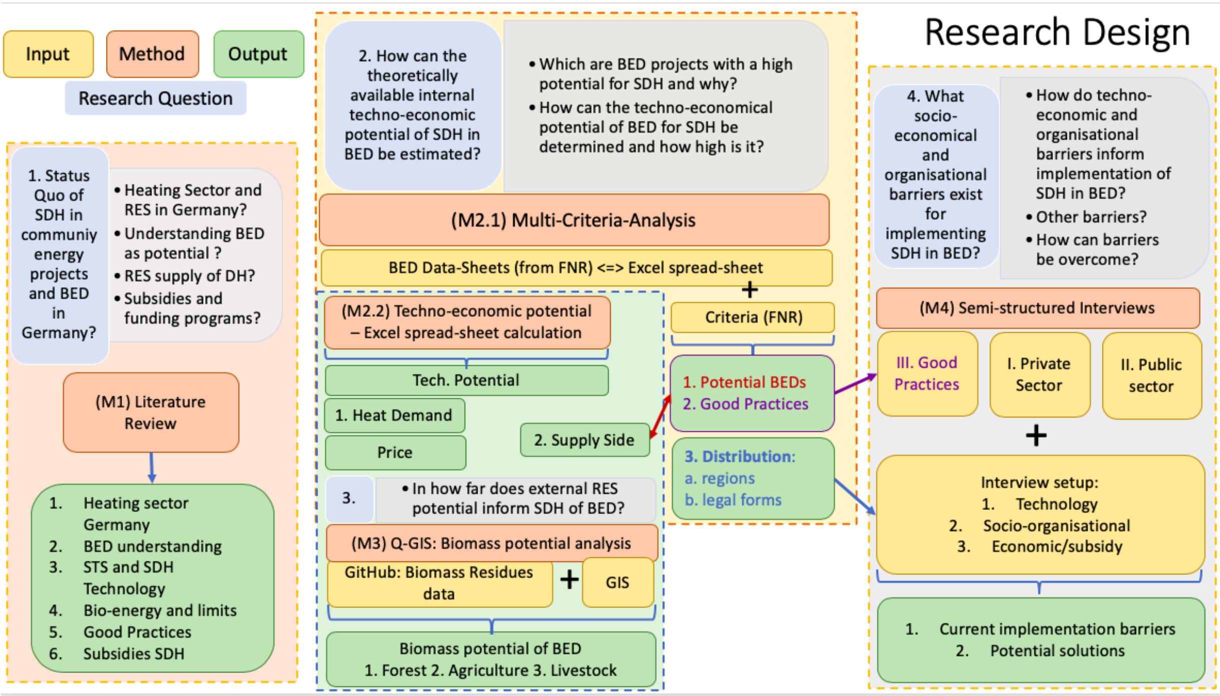

Figure 3.1: Overview of the research design and methodology applied

The second analysis presented in chapter 6 aims to answer the sub-research question on the external technological potential and was tackled with a method of **(M3) Q-GIS biomass potential analysis** - which is a three-fold estimate of the specific external biomass potential of each BED.
The last analysis seeks to answer the fourth research question in chapter 7. It is displayed on the right side of Figure 3.1 based on the last method applied, the **(M4) semi-structured interview**. This method analyzes the implementation barriers of SDH and other RES into BED on technological, decision-making and economical levels through seven expert interviews in three different categories.

Below, all methods are presented that were utilized throughout the thesis in order to answer the (sub-) research questions. Each method presented in detail in its corresponding chapter. To better understand the full analysis based on the sub-analyses, it is recommended to read each analysis directly after the explanatory description of its respective method.

3.1.1 Literature review (M1)

The literature review considered literature discussing Bioenergy-villages (BED) with a particular focus on those supplying their energy with bioenergies from Solar-thermal systems (STS) and solar district heating (SDH). Further consideration was given to literature examining how to bring the potential of these two renewable energy sources (sun and biomass) together. The literature analysis of current BED cases revealed that the field of BED is not widely examined yet and would merit from expansive further research.

3.1.2 Multi-Criteria Analysis (M2.1) - Excel spread-sheet

The Multi-Criteria-Analysis (MCA) aims to provide a tool that helps to quantitatively evaluate the different BED. The MCA is for the most part based on data from the Germany's agency for renewable sources (FNR - "*Fachagentur für nachwachsende Rohstoffe*") that comprised information on data-sheets of one to three pages enabling me to conduct an analysis of the supply and demand side potential of the acknowledged BED and non-acknowledged or planned BED (pBED). Based on the data-sheets, an Excel spread-sheet was created containing information on the locality (coordinates, postcode), federal state and size of the district heating system (derived from households residents). Moreover, information on the supply-side of the 159 BED and 45 pBED could be obtained. Overall, the following information could be retrieved: electrical and thermal installed capacities of bioenergy (biomass and biogas) conversion units; installed capacities of photovoltaics (PV) , wind, thermal energy storage, organic rankine cycle; and information on the supply- and connection-rate of the villages. Consequently, this information can be used as criteria in combination with the framework conditions to describe the technological potential of BED for alternative RES such as SDH. Section 5.1 provides an in-depth description of this methodology.

3.1.3 Techno-economic potential analysis (M2.2) - heat demand assessment

Based on the information obtained for the MCA and spreadsheet, the technological potential regarding the demand and the supply side of the BED and pBED for STS and SDH could be determined. Based on this, annual household and resident demands for warm water usage could be extrapolated. On the supply-side, information on biomass capacities as well as biogas capacities in combination with years of installation was used to understand the potential for SDH. Section 5.1.5 provides an in-depth description of this methodology.

3.1.4 GIS-based spacial analysis (M3) - BED's biomass potential analysis

In order for BED to become renewable energy villages at some point, the external RES potential needs to be taken into account in the planning and engineering process of an individual BED-specific energy system. The measure of bioenergy acts as the most telling indicator of value for BEDs, yet it is also the least determinable due to lacking information. Based on the Geo-Information-System (GIS) and data on different residue or second-generation biomasses in Germany's districts, an analysis of each of these sources of biomass of each BED was conducted. In combination with information on solar irradiation, average temperature and wind speeds should inform the energy system planning of each BED. Section 6.2 provides an in-depth description of this methodology.

3.1.5 Semi-structured interviews (M4) - socio-organisational barrier analysis

In the last and third analysis (see 7), primarily the socio-organisational, but also the economical and technological potentials were assessed by conducting a barrier analysis in the form of semi-structured interviews. For that, a target group of seven interviewees from public and private institutions and Good Practices related to BED, SDH and STS were interviewed. The data collected from the interviews was organized in such a way as for conclusions to be drawn from it. Section 7.3 provides an in-depth description of this methodology.

3.2 Philosophical framework of my research

The intention of adding this chapter to my thesis is to present some of my philosophical standpoints and to give insight into my perspective on our world. I do this to argue for how the use of (energy) technologies must go hand-in-hand with societal - or even cultural - progress. I also aim to highlight the opportunity I see for this combination to manifest in community energy projects such as Bioenergy-Villages as heart of this thesis. Today's modern world's "Sustainable Energy Planning" practices should reflect and display an understanding of the marginally questioned paradigm of a perpetually growing economy and how this is connected with the way we develop and use our (energy) technologies. Just as other policy-makers, scholars and activists that question the dominant capitalist model, I do call for "alternative lifestyles and a fundamental transformation of the economic system".[Rommel et al., 2018] The growth of the world's economic system is largely based on the (still) increasing extraction of fossil and nuclear fuels. Germany, as a national sub-system of the modern world with its growing economy, is highly dependent on a fossil-fuel based energy system, thus serving as a good example of this paradigm I call into question. Taking this into account, I will in the following outline philosophies and conceptual frameworks that are relevant for a ecologically and socially sound future based on sustainable energy systems.

The first concept is an **environmental philosophy** way of thinking called **Eco-Modernism** that assumes that nature can be protected through the optimization of the efficiency of technologies can perpetually be increased until a "decoupling" of the anthropogenic impact from nature is reached. [Ecomodernism]. Eco-modernism is rooted in the western industrialized world and places great trust in the infallible western industrialized world. Eco-Modernism intends to find solutions to our problems by means of (technological) innovation based on (i) a growing economy and (ii) "problem-solving capacity of technological progress" [Grunwald, 2018]. Grundwald, professor of philosophy and physics, and also director of the ITAS ("*Institute for Technology Assessment and System Analysis*") [KIT - ITAS] in Karlsruhe, Germany, criticises the Eco-modernist approach by stating that this approach assumes the ecological crisis can be overcome by technological progress and its acceleration only while "ignoring the ambivalence of technology and the issue of unintended side effects."[Grunwald, 2018]. In Europe, Eco-Modernism is the basis for "Green Growth", which usually represents a paradigm that focuses on replacing old (fossil-fueled) technology with supposedly green technology continue the design of our societies persisting on perpetual economic growth. The Eco-modernist / Green Growth approach also has followers among European green thinkers. For instance, Ralf Fücks – former director of the Heinrich-Böll foundation – who believes, or 'rather hopes', in a truly sustainable future through Green Growth. R. Fücks stated that in order to not "lose the race against the ecological crisis" we (humanity) need to rely on the hypothetical assumption that "innovative potential of modern societies is unlimited" which is as to Fücks what we (humanity) may "hope" for. ("*Darauf ist zu hoffen.*"(sic)) [Kiderlen et al., 2011, p.6]. Having such trust in technological advances brings about the notion of having "hope" in humanity's future (or at least in humanity's future along our current course). This understanding of "hope" is interpreted by Grunwald [2018] as if we are "betting" on merely technology-based scenarios assembled by blind trust in technological progress. If we do so, we will be very likely disappointed. Instead, he proposes, to use our technologies in a responsible, ethical way, taking options based on a trust that is more than purely technology-centric into consideration [Grunwald, 2018].

Another concept is described in the recently published book "Limits" by Giorgos Kallis[Thinkbelt, 2019]- professor of **Political Ecology** scientist at the Autonomous University of Barcelona. G. Kallis calls for self-limitation alluding to the physical planetary boundaries that were already described in 1972 in the book "Limits to Growth" by the Club of Rome and a researcher team around Meadows et al. [1972]. Acknowledging the planetary boundaries, scholars – such as G.Kallis - developed a conceptual framework called **Degrowth**, which is fundamentally agnostic with the paradigm of infinite (material and economic) growth and calls for a reduction of our societies' energy and resource metabolisms [Kallis, 2011]. The main thought behind Degrowth is that the Eco-Modernistic approach "bets" on the belief that technological advancements will eventually allow for the absolute decoupling of environmental impact (for instance carbon dioxide emissions) from technological expansion and economic growth. 'Decoupling' refers to the eventual separation of two currently interdependent phenomena, in this case environmental impact and economic growth. This framework claims that technology will eventually become cleaner and greener to the point that it disconnects or decouples from the environmental impact. [Jackson, 2009] points to the improbability of this decoupling happening, as it was hardly observed among the environmental impacts caused by our technologies. This does not mean that we should not make use of (certain) technologies.

According to Ivan Illich – a technology philosopher – we should only make use of technologies that we can co-live with. This is what Illich [1981] calls convivial tools (in this context '**Convivial Technologies**'). Illich also speaks of a technological threshold that, once crossed, leads to more environmental and social burdens that will be too heavy without further satisfying of our needs. As an example for convivial technology, the bike is often mentioned. Bikes are based on a certain simplicity and do not require many resources, but still enable people to be transported quickly in a very resource-efficient manner. Another benefit lending to the co-living nature of bikes is that they increase the user's physical activity, which contributes to physical health, something that is of the utmost importance, especially during today's global context characterized by the onset of the COVID-19 pandemic.
The former PhD-student of the Planning Department at Aalborg University Xue [2014] conducted research on Eco-Villages as a foundation of a Degrowth society. She argues that we, as planners, should be aware of 'bio-economics' by, first, taking the biophysical capacities of the system we live in into account, second, acknowledging the improbability that economic growth can be decoupled from environmental impact through mere means of technology [Xue, 2014]. Further, she argues that the development of an urban energy system should be informed bio-regionally, which encourages the development of local renewable energy systems by means of local RES. Further, Xue [2014] argues that we should work on political re-localization, which can be understood as the decentralized governance of small-scale (energy) systems.

Conceptual frameworks and Sustainable Energy Planning
I consider the epistemology of my investigations and my research positions themselves to be agnostic to the Green Growth approach. I am certainly disagreeing with Fücks' unconditional belief in the infinity of – technological – innovation. I think that "betting" on Green Growth and "hoping" for technological progress and absolute decoupling of environmental impact from economic growth could likely turn out to become humanity's biggest fallacy. For me, this means that we as sustainable energy planners should not deny the use of technology as such – but we should have a look at and be aware of the conviviality of our technologies. I am of the opinion that we as sustainable energy planners have the responsibility to plan according to this bigger picture while coping with questions arising from the growth paradigm and the expectations of technological progress. I think that we should not only assess and compare the impacts of different (RES) technologies, but we should be doing so as Grunwald [2018] describes: "against the backdrop of the 'big questions'".[Grunwald, 2018, p.9] In this case, this backdrop includes the marginally challenged growth paradigm and our expectations of limitless technological progress. As participants, actors and planners in the global energy transition I think that we are responsible to develop our own local, autonomous energy transitions. For the case of central Europe and Germany, this is most likely to be started with Bioenergy-Villages by developing alternative socio-organizational and technological paradigms in terms of using convivial technologies. I consider BED to be at the crossroads of those tending to question the

growth paradigm (e.g. BED Siebenlinden) and those putting their faith into Eco-modernism. Consequentially, BED are especially interesting to further enhance a just energy transition on both a convivial-technological [Illich, 1981] and political re-localized level [Xue, 2014], both of which can be subsumed under the concept of the "democratization of technology" [Kerschner et al., 2018] happening against the backdrop of the paradigm of perpetual economic growth.

4 | Theory: Bioenergy-villages and solar district heating

This section seeks to provide background knowledge and contextualize the following three analyses by tackling the first sub research-questions:

What is the status quo and underlying frameworks of Germany's heating sector, it's supply by different renewable energy sources, particularly biomass and solar thermal as well as the the status of Bioenergy-Villages today?

4.1 Introduction to the research subject: What are Bioenergy-Villages?

Bioenergy-Villages (BED - "*Bioenergiedorf*") are basically villages or communities that to a large extent self-supply their demand of electricity, domestic hot water (DMH) and heating primarily by the means of Bioenergy - which can be sub-categorized into biomass (BM) and gasified and fermented biogas (BG). Germany's agency for re-growing resources (FNR) has two published lists with (a) acknowledged BED and (b) non-acknowledged BED - the latter are BED under development [Fachagentur für nachwachsende Rohstoffe, b] - to which I henceforth refer as 'planned BED' (short 'pBED'). The idea behind the collection of BED is to show good practises to other communities and/or villages to profit from the existing experiences and to enhance Germany's "*Energiewende*" toward renewable energy sources (RES) on a local level. According to IBEG e.V., an association named "*Institute for Bioenergy-Villages Göttingen*" that has been accompanying the BED movement for the last two decades, the BED's contributions to the Energy transition is twofold. First, they enhance the CO_2-neutral energy supply. Second, they contribute to autonomous rural development and thus improve rural community energy independence. [IBEG e.V., 2015]

The **FNR's definition** of BED is to "switch the predominant share of the heat and electricity supply to be based on renewable energy source biomass", [Fachagentur für nachwachsende Rohstoffe, b] thereby covering at least 50% of their energy (electricity and heat) needs from regionally produced 'bio-energy'. Further, FNR's definition of BED incorporates, on an organisational level, the local residents into the decision-making processes carrying the values of project (see also subsection 7.2.1 on operation corporation of BED). The FNR explicitly indicates in their definition that the "supply of heating and electricity generated from biomass can be supplemented by the usage of other renewable energy resources" [Fachagentur für nachwachsende Rohstoffe, b] for a village to get the FNR's official BED-acknowledgement.

On the other hand there, is the IBEG's definition of the BED that slightly differs from FNR's, but as both definitions exist they should both be considered when working with BED. The **IBEG's definition** generally agrees with the FNR's definition, and is made up of the following four items:

1. The village generates at least as much electricity by means of biomass as it demands.
2. The heat demand of the village is **at least to 50%** supplied by means of **biomass**, preferably by combined-heat-and-power (CHP) plants (more energy efficient)
3. Ownership structure: The BED's bio-energy facilities implemented should be at least 50% the property of local heat-consumers and local farmers supplying biomass fuels. As many involved parties as possible should own shares of the bio-energy facility.
4. The biomass must not originate from (corn) mono-cultures and genetically modified plants. In this context (corn-)mono-culture is understood as the crop sequence only consists of corn.

4.1.1 Reasons for Bioenergy-Villages movement

Overall, the FNR mentions five means reasons that favor the concept of and support the visions and idea behind BED: [Fachagentur für nachwachsende Rohstoffe, c]

1. **Finiteness of fossil and nuclear fuels**: The core argument here is what is expressed by the Club of Rome in the "Limits to Growth" [Meadows et al., 1972]. The BED puts forward the reasoning that humanity will run short on fossil fuels and uranium by the end of the 21^{st} century.
2. **Climate Change and greenhouse effect:** In 2019, the Earth's climate has warmed by 0.95C above the 20^{th} century average [Lindsey and Dahlman, 2020]. Climate scientists forecast an increase between 2 and 6C by the end of the 21^{th} century.
3. **Independence from imports:** Fossil and nuclear fuels are imported to Germany from democratically unstable regions. Germany's buying power is enormous and could so potentially lead to high profits in non-democratic structures.

4. **Structural change in rural areas:** The offer of workplaces is on decline in Germany's rural areas and people accumulate rather in urban areas and cities. Young, educated people move away and many rural areas face depopulation. BED create job opportunities, work, long-term stable energy prices and a common project.

5. **Quality of life and identification:**: Generally, in rural villages a lack of common tasks is often observable. BED have the potential to have a positive impact on the community's self-confidence.

Reinforcing the above points, IBEG e.V. [2015] states in the **Declaration of Jühnde**, published by a union of BED, that being a BED goes beyond using RES technology. It is also about contributing to climate protection while securing a community's energy supply using efficient technologies such as CHP, supporting the energy systems' decentralisation and thereby increasing the community's autonomy. To do so, BED can be flexibly controlled to contribute to the local creation of value and ideally support the share-holding and participating community. [IBEG e.V., 2015]

4.1.2 Operating corporation and legal forms of Bioenergy-Villages

In order for BED to legally generate, distribute and sell energy, it is required to found an operating corporation ("*Betreibergesellschaft*") through the submission of different legal forms with different characteristics for each action (energy generation, distribution and sale). According to FNR, only the legal forms are suited for BED that do not have 'full liability' ("*Vollhaftung*"), which means that a person behind a legal entity cannot be made fully liable with their own private property [Fachagentur für nachwachsende Rohstoffe, a]. Consequently, the legal forms can be either differentiated according to their type of liability (private or not) or their decision-making processes. An overview of the existing legal forms in Germany is presented in Table 4.1 below - together with an information (right column) on the type of liability. The Fachagentur für nachwachsende Rohstoffe [a] states that the legal form should be decided upon by having a maximal legitimization in the village assembly. In a founding assembly, the residents of the BED shall find their optimal case-specific legal form for each operating corporation.

The conceptual idea behind communizing the operating corporation is, ideally, to have members of all stakeholder groups - such as, most importantly, the heat-consumers, but also local farmers as supplying the BED with fuels - represented in the corporation. On one hand, there are the heat-consumers that own (partially) the energy system which makes them also heat-deliverers. Naturally, as heat-consumers they have an interest in low heat-prices. On the other hand, the farmers are interested in a high biomass-price. Having both groups represented in the operating corporation moderates both the heat-price and biomass-price, allowing for an appropriate price for each to be reached, creating overall value for the project. Both sides cannot unilaterally enforce their will power, because in the phase of the heat-contracts' negotiations neither the heat-consumers nor the farmers would sign a long-term contract. [Fachagentur für nachwachsende Rohstoffe, a] Usually, an operating corporation of the BED has the following six

German acronym	Name of legal form	English (UK) analogue	liability type
GbR	*Gesellschaft bürgerlichen Rechts*	'non-trading partnership'	private
OHG	*offene Handelsgesellschaft*	'general partnership'	private
KG	*Kommanditgesellschaft*	'private limited partnership'	private
GmbH&CO KG	*Gesellschaft mit beschränkter Haftung*	'private limited company'	not private
eG	*eingetragene Genossenschaft*	'registered cooperative society'	not private

Table 4.1: Overview of legal forms in Germany generally as operating corporation of Bioenergy-Villages; Source: [Fachagentur für nachwachsende Rohstoffe, a]

main areas of responsibility: contracting of the delivery of hot water and biomass fuels, securing funding and discussion with financial institutions, planning project concepts and approvals, execution of the construction work, employing staff for commercial and technical division and completing the commercial operational management.

4.2 Status quo of the Bioenergy-Village fuels

Bioenergy and its sub-fuels are into the context of the BED and explain occurring problems and the biomass potential of Germany.

4.2.1 Biomass and biogas - Bioenergy-Villages' fuels

When the term bioenergy is mentioned, usually different types of resources, technology pathways and areas of application are referred to. Technically, bioenergy can be (I) gaseous in the form of BG or bio-methane (henceforth both referred to as 'BG') (II) liquid and used as fuel in power plants or for transportation and (III) solid biomass in forms of split logs, woodchips or straw-pellets that are usually combusted to supply heat and/or electricity. The main commonality between these forms of bioenergy is that they are all forms of plant-stored solar energy. Therefore, this chapter aims to give a short introduction and overview of what is meant by utilizing the terms bioenergy, and its sub-categories of 'biomass' BM and BG, which are the main bioenergy used in BED. The resources for bioenergy primarily comes from plants specifically cultivated for the purpose of generating energy - such as corn, rape, sunflowers, and palm oil [Umweltbundesamt]. These crops are also edible, hence their being referred to as 'first generation biomass' [Lee and Lavoie, 2013]. As a consequence of the variety of plants that are suitable for producing bioenergy, their origin can be local, but are exceedingly global and bioenergy can be delivered via the global trade currents to Europe. This is, in particular, the case with BM, which is better and more easily transported than BG due to its solid state. Following the BED's definition (see subsection 4.1) and to secure locality, only plants endemic in Germany are relevant for this research. Germany's endemic BM can be split up into the following three main categories [Umweltbundesamt]:

1. Fast-growing woods: especially cultivated on agricultural farms
2. Wood from forestry
3. Biogene residues from agriculture and forestry, households or industry

4.2.2 Biomass potential in Germany

Differentiating between **theoretical and technical potential:** There are various forms of measuring the potential of energy resources. The most important ones are the theoretical and the technical potential. The theoretical potential describes the potential capacity for producing biomass, or biomass potential (BMP) of a a specific region (Germany) and a specific time-frame, and constitutes the theoretical maximum potential. The technical BMP includes restrictions based on technical, structural, legal or societal aspects. Thus the technical BMP can be defined as materially and energetically usable biomass within a specific region and time. [Brosowski et al., 2015]

In general, BM and thus BG forms an inexhaustible energy carrier fuel, assuming it is being grown and harvested sustainably. The BM growing annually world-wide outstrips humanity's energy consumption by a factor of five to six - which depicts the maximum theoretical potential. Self-evidently this amount of energy cannot be harvested at a single time due to ecological, economical and technical constraints. However, the remaining technical BMP is still remarkable. Germany's domestic biomass is estimated to have a contribution of up to 26% by 2050 of the country's total primary energy usage in all three sectors - heating, electricity and transportation. [FNR, 2016, Brosowski et al., 2015] This number is derived from the goal of the German government, which is to reduce the country's total energy consumption from 13,645 Peta Joule (PJ) (in 2015) to 7,000 PJ (in 2050). The 26% contribution of bio-energy is equal to 1,819 PJ in all three energy sectors and is categorized as follows: First, BM from hardwood such as residues from forests and landscape conservation and scrap wood will cover a share of 10% respectively 697 PJ - approximately one third of this source is unused today and available for future usage. Second, the FNR's calculation states that biomass-energy from agriculture (corn, raps, fast growing trees and agricultural residues can cover 988 PJ - of which today only one-third is used. Third, livestock residues such as organic waste and sludge form the last group with a potential of 134 PJ which is already largely exploited today. [FNR, 2016] This leads us to the amount of Germany's unused BMP depicted in the following chapter.

4.2.3 Unused biomass potential in Germany

Today, the non-utilized BMP in Germany concentrates on only a few biomass categories and shows to have a comparably high amount of energy. The German unused residue BMP on different annual bases is depicted in Table 4.2 below. The total amount of unused BM from residues is at 30.9 M tons/year - of which the majority (95%) falls into the three categories of (i) unused residues of forests (38%), (ii) animal excrement (29%) and (iii) crop straw (27%). Note: approximately 4% of scrap wood from landscape care and some other minor "other residues" are not depicted in the table, since a law forbids its usage [Brosowski et al., 2015].

Table 4.2: Technically unused residue biomass potential of Germany [Brosowski et al., 2015]

Type of Biomass	Million tons/year	Peta Joule/year	Relative Share	Year of Data
Total	30.9	448 PJ	100%	mixed
Wood and forest residues	11.88	218 PJ	38%	2012
Animal excrement	9.10	66 PJ	29%	2010/2013
Crop straw	8.47	141 PJ	27%	1999-2007

4.2.4 Indirect land use change - iLUC : energy-biomass versus food production

Indirect land use changes (acronym often referred to as "iLUC") are the result of displacement effects caused by additional demand for land for the growth of BM. In this case, the added BM demand displaces land that was otherwise used for food crop production to other areas.. The iLUC-effect is a considerable factor in the environmental impact of BE fuels, since the displaced food production is a "new" demand. That demand is often covered by turning whole ecosystems into agricultural crop land which results in additional greenhouse gas emissions since old ecosystem disappear [Umweltbundesamt].

Further, the land requirements of animal breeding are comparably high. "Overall, animal breeding and foremost the meat productions especially requires a high amount of areas" [Jering et al., p.35], and this land requirement is more for animals than it is for plant-based aliments. In the rich parts of the world ("Global North"), the demand for animal-based products is the highest in the world. [Jering et al., p.34] However, the demand of these land-intensive products is declining in the Global North. Theoretically, if the meat consumption of the OECD-countries continues declining and was finally reduced by 30%, the land pressure would be decreased and around 30 million hectares (ha) of cultivatable farmland would be released. [Jering et al., p.36] That could be used for (sustainable) biomass production to be used in RES, or for solar (thermal) applications.

4.2.5 Space energy efficiency of biomass versus other renewable sources

Different RES technologies have a different specific demand of land area. This presents a conflict between the different technologies based on land availability, especially with regards to fertile land as depicted above. According to Germany's Federal environmental agency, several studies have shown that the "space efficiency" of solar thermal energy or also RES in electricity generation such as solar photovoltaic (PV) or wind-turbines is greater than biomass. Biomass's high space requirements paired with the population density of the often rural areas in which biomass is produced, cultivated biomass in central Europe (or Germany) can only make up a limited share of the energy supply [Umweltbundesamt] as described in the subsection on the BMP 4.2.2.

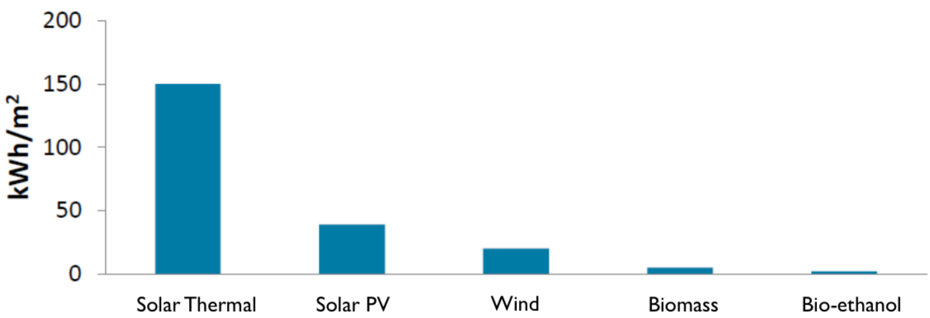

Figure 4.1: Annual energy yield per m^2 of land used for different renewable energy sources in northern Europe. Source: [Sørensen et al., 2012]

The above Figure 4.1 depicts the results of a study displaying the differing RES' specific land use efficiencies yields in Northern Europe - assuming that solar thermal has an efficiency of 15%, solar PV use 1/4 of the STS energy. The wind value is derived by assuming an $8MW/m^2$ energy intensity and 2400 full-load hours. The biomass output is derived by assuming 1000 $tons/km^2$ with a calorific value of 15 GJ/ton.

4.2.6 Biogas in combined heat and power in Germany

In 2015, bio-gas power-plants supplied 25 TWh_{el} electricity to Germany's grid [Stocker, 2015]. The number grew to between 32 and 33 TWh_{el} annually and stagnated thereafter [Daniel-Gromke et al., 2020]. BG power plants are generally able to supply heat as well as electricity without major fluctuation by using combined-heat-and-power plants (CHP) technology that increase their efficiency. The high growth rates and its ability to balance the fluctuation of other RES generation are the advantages of BG in Germany and make it - at first glance - a 'success story' [Stocker, 2015]. However, two downsides of BG facilities are pointed out subsequently. First, BG facility operators produce heat and electricity using the fuel around the clock, despite the most efficient use of the fuel being to use it to generate energy on an as-needed basis to counteract fluctuations of other RES. BG is technically storable, theoretically on the short-term (hourly/daily) and over longer period of time (months/seasons). As a consequence, it would be ideal to store and use BG when it is needed - for instance in winter-times to fuel a DH system. Several storage options exist, such as in (partially existing) small gas storage on-site, or ,if refined before, in the German national fossil gas grid..[Stocker, 2015] Second, the high growth rates of BG are being criticised by environmentalists, food-producers and politicians [Stocker, 2015]. With the introduction of the EEG-law in 2000 (see also 4.7.1) the number of BG plants has been continuously growing, but since the EEG updates from 2012,2014 and 2017 the additional new BG installations have decreased. At the beginning it was believed that BG facilities should mainly process and refine residues from agriculture and the food industry into gas, but this has developed into a system in which out of the approximately 8800 BG facilities (end of 2018) [Daniel-Gromke et al., 2020], approximately 80% were supplied by corn especially grown as *first generation biomass* in large mono-cultivated fields. In 2015 in Germany, the area for these types of mono-cultures were at 750,000 hectares (ha) leading to the suppression of other food products. The environmental pressure by the mono-cultures has been a direct consequences of this "biogas-boom". [Stocker, 2015] Other scholars found the situation of biogas production facilities in Germany to be at a cross-roads after two decades of subsidies and envision a future in which biogas systems are integrated into a circular bio-economy based on biomass residues[Theuerl et al., 2019]. Ultimately, according to Germany's environmental agency and others, BG as refined biomass is required in an energy system that shall run 100% on RES while complimenting each other efficiently [Umweltbundesamt, Stocker, 2015].

4.3 Technology of Solar District Heating systems

Generally, a SDH system consists of large solar thermal collector (STC) fields that are integrated into either (i) a district or (ii) a block heating system with the aim of supplying heat for use in water (both for heating and drinking) to residential or industrial areas. This chapter points out the different potential sectors and the possible combinations with other RES technology.

4.3.1 Potential sectors for Solar District Heating

In total three different sectors for SDH are identified. [Pauschinger et al., 2019b] These sectors are (i) densely populated urban areas, (ii) Energy Villages - most similar to the BED and (iii) quarter level.

Densely populated urban areas

Big district heating systems in densely populated urban areas such as cities are today fueled by heat from CHP stations, heating plants or the utilisation of industrial waste heat. These are usually fuelled by fossil gas, coal, waste and/or biomass. On the one hand, the decarbonisation of the District Heating of cities presents to be a big challenge, while, on the other hand, it offers an efficient and cheap approach for a fast heat transition in urban areas. The integration of solar energy systems is described to be a big possibility to increase the share of renewable energy (RE) generation in such systems. An increase of solar thermal projects with sizes over 10,000 m^2 can be observed demonstrating that finding suited space in urban areas is possible. [Pauschinger et al., 2019b]

(Eco) Energy Villages

At the moment there are local heating networks emerging in so-called Energy Villages ("*Energiedörfer*") primarily in rural areas. At its core is the exchange of decentralised oil-fired heating against a local district heating system fueled with RES. A report argues that the combination of a solar thermal facility with renewable biomass fueled heating plants in big open rural areas forms a model of success [Pauschinger et al., 2019b]. The possibilities of organizing the operation of district heating in BED are vast. There are several cases where local citizens formed and founded energy associations ("*Bürgerenergiegenossenschaften*") to run the facilities. In other cases the operators are owner-operated municipal enterprises ("*Eigenbetriebe*), municipal utility companies ("*Stadtwerke*) or regional suppliers ("*Regionalversorger*"). [Pauschinger et al., 2019b] (see also section 7.2.1)

Neighborhood quarter level and housing industry

The biggest share of DH in Germany supplies larger apartment buildings and multiple dwelling units connecting parts of cities on a neighborhood quarter level. The structural change in the cities' DH towards RES makes a contribution to the goal of a climate-neutral building inventory. Many neighborhoods do have own local district heating networks that are operated by energy-suppliers, contracting companies or the housing industry. Also, in these cases large-area solar thermal is applicable - though naturally finding the areas for larger collector fields might prove to be more difficult. However, planning on a quarter or neighborhood level usually enables more cost- and material-efficient solutions. [Pauschinger et al., 2019b]

4.3.2 Combining Solar District Heating with other renewable sources

Solar Thermal Systems (STS) that supply District Heating (DH) "can technically be combined with all other fuels for district heating" [Sørensen et al., 2012] so consequently it will depend on the specifications of the district heating system and on environmental and economical considerations. The production price for SDH in Northern Europe is at 3 €-cents/kWh_{th} and in Southern Europe at 2 €-cents/kWh_{th} [Sørensen et al., 2012] - these are usually the competing prices for heat from other (RES) sources.

Combining SDH and biomass boilers

BM boilers have a marginal heat production price of around 2 - 3 € cents / kWh$_{th}$ - whatsoever this price is more volatile depending on the local market. Two considerations need to be taken into account. First, in order to cover the summer heating load, a thermal storage tank is needed. In this way energy can be harvested during the day and used in the night. In the winter months, the accumulation tank will also permit the BM boiler to run on a fixed load, so that it does not need to be ramped up and down many times, thus increasing the life time of the boiler.[Solarthermie.net, a] Secondly, in order to turn the BM boiler completely off during the summer months, the STS needs to be designed have a solar fraction of around 100% during that period. An additional small back-up boiler running ideally not on fossil fuels, but for instance on bio-gas should be installed in parallel as depicted in Figure 4.2 below. [Sørensen et al., 2012]

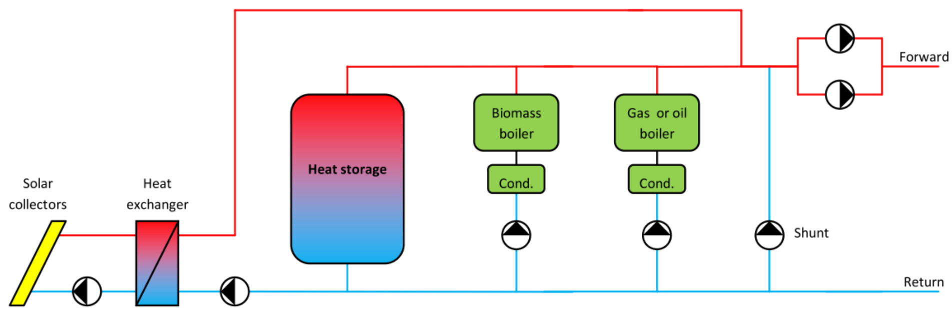

Figure 4.2: Schematic example of the combination of solar thermal collectors with biomass and biogas boilers and a thermal storage tank (Source:[Sørensen et al., 2012] cited from PlanEnergi

Already twenty years ago a paper for the case of Austria (context very similar to Germany) which describes the seasonal mismatch between solar energy supply (higher in summer) and solar energy demand (higher in winter). It is described how long-term (seasonal) Thermal Energy Storages (TES) could potentially fill the gap between supply and demand, but that 'bio-genic fuel sources' - to what I refer to as biomass - in "the form of firewood, bark and wood chips from the forests and the remnants from the wood processing industry are an obvious form of 'natural storage' for solar energy" [Faninger, 2000], as they are locally available and can easily be stored, transported and grown again. Thus the 'storability' and flexibility of biomass can support an optimal conversion with STS for heating usage as an auxiliary fuel.

Combining SDH with environmental heating

A direct combination of solar thermal and environmental heat (heat pump) is technically possible. Environmental heat supplied from the air, soil or groundwater can be directly combined with the solar system. Further, an indirect combination is possible with which the STS heats up water in order to increase the yield of the heat pump, that is usually using environmental heat from the soil. This system allows a decrease in the size of the heat pump design while increasing the efficiency of the STS due to its ability to run on lower temperatures. This indirect application is usually found as solution for individual households. [Solarthermie.net, b]

4.4 Status quo of heating sector supply in Germany

This chapter outlines the current status quo of the heat supply of Germany's heating sector by Renewable Energy Sources (RES), which fraction reached an overall historical high of 14.5% in 2019 regarding the final consumption of heat. This chapter subsequently first displays a general overview of the heating sector and subsequently explains the situation of biomass, solar thermal and heat pumps.

4.4.1 Supply of heat by renewable energy sources in Germany

In 2019, the share of RES utilisation in the final energy consumption for heating and cooling in Germany increased by 0.2% to 14.5% reaching an all time high in the same year. The 0.2% correspond to an absolute increase in RES by approx. 4% to 176.4 TWh_{th} in 2019. At the same time more fossil fuels were used in the heating sector due to a colder winter, so the RES share did only increase by 0.2%. [Umweltbundesamt, 2020]

Figure 4.3 displays the distribution of the supplied heating by RES in Germany in the year 2019. About two third of it is supplied by solid biomass in different sub application forms. In total, solid biomass had the lion share of 116 TWh_{th} and is consequently the most prominent renewable energy source for the heat supply in Germany. BM is being followed by BG that has a share of 13 TWh. Meanwhile solar thermal heat supply increased by 4% (compared to 2018) to 8.5 TWh_{th} annually. The last heat source is environmental and geothermal heat that reached an all-time high with approx. 16.0 TWh_{th} (+8% compared to 2018).

4.4.2 Biomass in German heating sector - status quo

In 2019 Biomass heating made up 86% (including biogas and residuals) - respectively 152 TWh_{th} making it the most important source of energy for renewable heating in Germany. In 2019, the overall energy usage of biomass (pellets and energy-woods) was approx. 8% higher (2.3 M tons/year)than the consumption of the prior year (2.2 M tons/year). In the same year also the amount of pellet-boilers sold increased by 4% respectively 35,000 units - of which 16,000 were central heating facilities. Thus, by the end of 2019 Germany had around 492,000 pellet-boilers installed - out of which 289,000 were central heating facilities. [Umweltbundesamt, 2020]

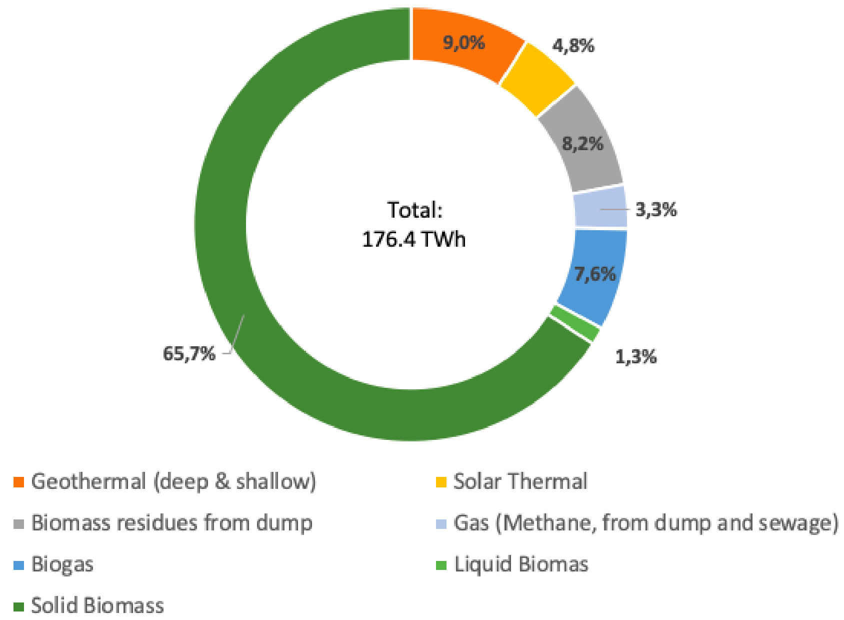

Figure 4.3: Heating from Renewable Energy Resources in Germany (in 2019) - Total TWh_{th} Own depiction - Source: [Umweltbundesamt, 2020]

4.4.3 Solar Thermal Heating in Germany - status quo

Since 2012 the annual new role-out capacities of solar thermal collectors have been decreasing. In 2019, only 511,000 m^2 of new collector area was installed, which is according to the German organization of Solar Economy ("*Bundesverband des Solarwirtschaft e.V.*") even less than in 2018 (573,000 m^2). Consequently, if including dismantling of old STS overall 19.3 M m^2 collector area was installed in Germany in 2019. The STS capacity in Germany is stagnating, basically because dismantling and built-up balance each other out, which led in combination with less sun hours to an overall production of 8.5 TWh_{th} in 2019 [Umweltbundesamt, 2020].

4.4.4 Geothermal and environmental heating (heat pumps)

Germany's Federal Association for heat-pumps registered an increase by 86,000 HP respectively 2% for 2019. Out of these HP 77% were taking their energy from the ambient air and the remaining 23% from ground heat[Umweltbundesamt, 2020]. In 2019, in total 16.0 TWh of geothermal heat was generated in Germany - which is 10% more (an equivalent to around 16,500 facilities) than the 14.8 TWh generated in 2018 [PlanEnergi and NIRAS].

4.5 Development of Solar District Heating in Germany

This section elaborates on SDHin Germany by showing first the past development of the technology and current status of the STS utilized in heating in Germany. Then, an overview of the existing applications is given.

4.5.1 Status quo and development of Solar District Heating in Germany

The following figure 4.4 presents the development of the cumulatively installed STC area over the past two decades. The graph subdivides into different type of groups that are supplied by SDH - which are industry, energy villages, district heating in cities and neighborhood solutions. The overall cumulative installed STC field area in BED (in the graph blue and referred to as "Energy villages") is the focus of this thesis and has been steadily increasing ever since around the year 2010. The last three years (2016 - 2018) one can see a slight increase in the overall installed capacity mainly due to the new capacities installed in 2018 in the Energy Villages. Further, the graph depicts an outlook for the role-out of STS based on the investigations of the company Solites from Stuttgart, Germany that forecasts an increase in new installed capacities until 2023. The subsection 4.5.3 elaborates on the prognosis of the role-out potential for SDH in Germany.

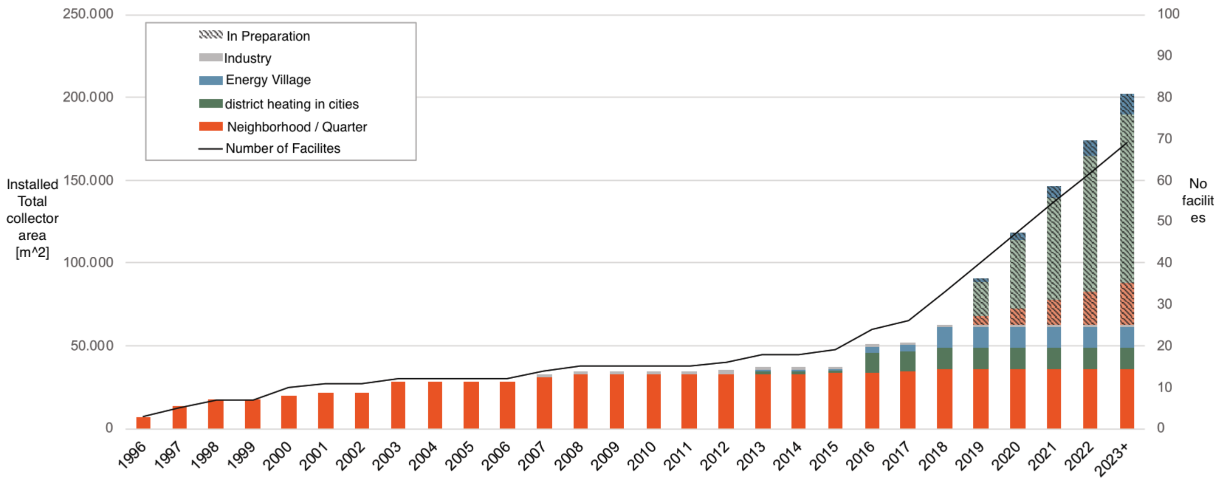

Figure 4.4: Development of Solar District Heating in Germany distinguished in the categories: i) Industrial, ii) Energy Village, iii) Urban District Heating, iv) Quarter/Neighborhood district heating [Pauschinger et al., 2019a]

4.5.2 Existing solar thermal heating plants in Germany's district heating

By May, 2019 there were in total 34 free-standing Solar Thermal Systems (STS) with an overall capacity of 44 MW_{th}, respectively 62.700 m^2, installed in Germany. According to Pauschinger et al. [2019a] there were 19 MW_{th} (23,200 m^2) in the process of implementation or planning. Eleven out of these 34 STS facilities in operation were built in the phase between 1995 and 2012 and financially supported two former research and development funding programs: "*Solarthermie2000*" and "*Solarthermie2000-plus*". [Pauschinger et al., 2019a]

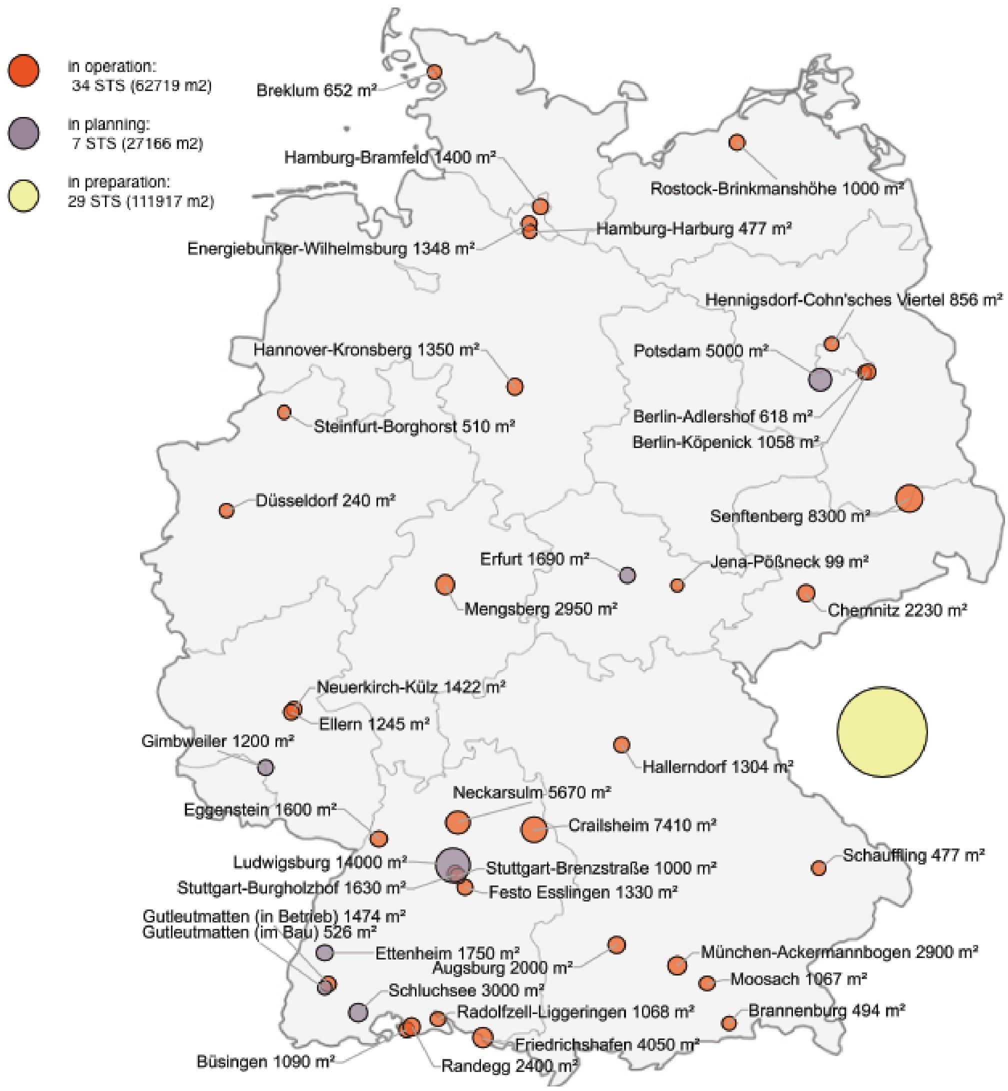

Figure 4.5: Overview of the in 2019 existing Solar District Heating 34 projects in Germany and the ones in preparation (29) and planning (7) - Source: [Pauschinger et al., 2019a]

In terms of the size of the collector field there are two milestones of STS in Germany. The first is the SDH of the city of Senftenberg in Brandenburg with an installed capacity of 8,300 m^2

illustrated by the biggest circle in the eastern state of Brandenburg in Figure 4.5 - subsection 'Good Practices' (see 4.6) further depicts the project. Secondly, the SDH of Ludwigsburg in Baden-Württemberg that has a planned collector area of 14,000 m^2 [Pauschinger et al., 2019a] is displayed in the south-west of Figure 4.5 that is under construction and is expected to start operation in May, 2020 [Stadtwerke Ludwigsburg-Kornwestheim, 2020]. According to information given by Solites as of 2019, in total 9 (Bio-)Energy-Villages do have a SDH with solar collector field sizes between 1000 and 3000 m^2 installed (I only know of two) - the source does not state how many are combined with BM boiler capacities. Five out of these nine SDH systems were implemented in 2018. [Pauschinger et al., 2019a]

4.5.3 Solar thermal growth potential in Germany

A research team Hansen and Vad Mathiesen [2018] concludes in their study that STS have a role to play in the future energy system so or so, mainly because of two reasons. First, they release the pressure from scarce resources - for instance biomass. Second, they help to supply heat at places where no alternative (other renewable) heating sources are available. At the same time STS are mostly interesting for smaller settlements (such as BED) and not for larger DH areas in dense urban dwellings because of the space requirements and the land prices. For the case of Germany, the same research team calculated that with solar thermal penetration of 20-50% the solar thermal potential for heating is at 15-60 TWh_{th} annually respectively 3 - 11 % of the total heat production.[Hansen and Vad Mathiesen, 2018] A study on Germany's heating transition concludes that 100 TWh_{th} of solar thermal heat is a feasible scenario for Germany within the next 25 to 35 years [Kunz and Kirrmann, 2016, p. 30]. It further states - also taking electricity generation by photovoltaics into account - that open areas and roof areas will not be the limiting factor for solar thermal energy supply in Germany to reach 14% (equivalent to 100 TWh_{th}) [Kunz and Kirrmann, 2016, p. 24]. Basically due to Germany's current funding and subsidy situation as depicted in Section 4.7.1 it is estimated that installed capacity of SDH is expected to grow threefold in relation to the installed capacity of 2018. A prognosis of the SDH's market development forecasted the number of facilities to double to 70 by 2023 which corresponds to a role-out of 95 MW_{th} respectively 135,000 m^2. According to the authors the prognosis is based on "concrete realisation, tender offers, planning processes and feasibility studies of large-scale solar projects" [Pauschinger et al., 2019a]. The integration of large solar thermal collector fields (<10,000 m^2) represent the with over 75% the lion's share of newly installed applications.

Anyhow, the growth rates of STS were too low to reach the goals set in 2015 by Germany's Federal Ministry of Economy and Energy (BMWi - 'Bundesministerium für Wirtschaft und Energie'). The BMWi set a scenario 'Renewable Energies' the energy-efficiency-strategy aims at increasing the solar thermal capacity from 3 TWh_{th}/a in 2008 to 80 TWh_{th}/a by 2050, while District Heating is supposed to be unchanged also at 80 TWh_{th}/a.[BMWi, Pauschinger et al., 2019a] Assuming that in the intermediate run the solar fraction is at 15% respectively 12 TWh_{th}/a. For that assumption it is required to install 30 M m^2 respectively a capacity of 21 GW_{th} of solar thermal collectors until 2050. This corresponds to an average annual new role-out 1 M m^2 respectively 0.7 GW_{th}. The overall required area is only 60 km^2 or 8x8 km. [Pauschinger et al., 2019a]

According to a presentation of a working committee meeting on "efficient cities" Erfurt in February, 2017 the potential for Germany's SDH for the year 2030 is to be 36 TWh_{th}/a - according to an BMWi/Prognos AG estimation from 2015. The same presentation also refers the Frauenhofer Solar Institute's prognosis from 2013 estimating a potential of 27 TWh_{th}/a by 2030 of which 17 TWh_{th}/a are expected to be installed in DH Systems.[Facharbeitskreis Effiziente Stadt and Ritter XL Solar, 2017] (Note: presentation retrieved via personal correspondence with a researcher from Lund Unversity)

4.6 Good Practises for Solar District Heating from the northern hemisphere

In the northern hemisphere, pre-assumingly under similar conditions as the BED in Germany several SDH projects are found that can serve as examples respectively Good practices. The Solar Fraction - the share of annual energy generation by solar technology - of these systems ranges between between 20% and 100%.

Drake Landing Solar Community, Canada - almost 100% Solar District heating: has 52 residents and is located in Okotoks, Alberta, Canada. The SDH systems consists of 800 solar thermal collectors on rooftops that provide a total aperture area of 2293 m^2 and can generate up to 1.5 MW_{th} and also a seasonal underground 'Borehole Thermal Energy Storage'. [Drake Landing Solar Community, a] In 2019, the SDH run 12 years reliably without any unplanned interruptions. In years, the solar fraction above 90% reaching an average of 96% in the period from 2012 until 2016. In the 2015-2016 heating season, the total (100%) heat demand for the houses was supplied by the CSHS.[Drake Landing Solar Community, b]

Marstal, Denmark has roughly 2,300 residents and is located on the Danish island of Ærø. Its heat is fully supplied by a District Heating (DH) system fuelled to 100% by four different types of RES: 50-55 % are supplied by solar collectors, 40% by wood-chips and approx. 2-3% by heat pump (HP). The remaining energy is covered by a bio-oil fuelled back-up boiler.[Co2mmunity, 2019] In total, 18,300m m^2 of STC are installed, 4 MW_{th} of wood-chip boiler and a 0.5 MW_{th} HP.[PlanEnergi] that bridges the load and is put to work when cheap wind energy is available in abundance. Further, two pit storage systems of 10,000 and 75,000 m^3 were installed as seasonal Thermal Energy Storages. The district-heating's ownership modes is a consumer-owned cooperative. [Co2mmunity, 2019]

In **Silkeborg, Denmark:** 11,000 residents are connected to the local DH network. Since the end of 2016 it is supplied a solar fraction of 20% by SDH that has the largest aperture field world-wide. In total, 156,694 m^2 respectively 12,436 solar collectors are installed in the SDH. With its peak capacity and and thermal storage of 64,000 m^3 the SDH produces annually approx. 80 GWh of energy. [Arcon Sunmark, b]

Dronninglund, Denmark: has a SDH with a collector field size of 37,573 m^2 installed in a total of 2,982 solar panels. The maximum thermal power from the field is 26 MW_{th} accumulating to an annual calculated energy amount of 17,453 MWh/year [Dronninglund Fjernvarme et al., 2014]. This is a solar fraction of approx. 40% of the annual heat demand[Arcon Sunmark, a]. Further, a seasonal TES was installed between 2003 and 2013 with a storage capacity of 60,000 m^3. The STS is backed up by CHP run on bio-oil simultaneously delivering heat and electricity for a heat pump. A base load of heating in this project is supplied by fossil gas. [Dronninglund Fjernvarme et al., 2014]

Senftenberg, Brandenburg, Germany: is a city with around 25.000 inhabitants in North-Eastern Germany in the federal state of Brandenburg in the region of Lausitz, that is know for its open-pit lignite mines. In total 10,000 households are connected to the DH of Senftenberg which is mainly fuelled by fossil gas and Germany's largest solar thermal collector field (2.2 ha) consisting of 1,680 collectors that generates during 1,700 hours annually around 4 GWh_{th}. [Kommunal Erneuerbar, 2016] The STS is able to deliver almost full base-load during the summer months. [Agentur für Erneuerbare Energien, 2016a]

Neuerkirch und Külz, Rheinland-Pfalz, Germany: Since 2016, a combination of a biomass power plant and a STS meets the annual total heat demand of 3.1 GWh of in total 140 households. The STS is thereby designed to cover 20% of the annual heat demand and to supply 100% of the base-load energy so that the two wood-chip heating plants can be turned off during the summer time. [Agentur für Erneuerbare Energien, 2016b]

4.7 Present subsidies, funding programs for Solar Thermal Heating in Germany

This section seeks to give an overview of the different fundings relevant SDH and BED in the course of this report.

4.7.1 German Renewable Energy Source Act - EEG-funding

The Renewable Energy Source Act (German "Erneuerbare Energien Gesetz", short 'EEG') is a law that was passed intending to promote the role-out and installation of electricity generating capacities in Germany based on Renewable Energy Sources (RES). The law primarily regulates the favored use of electricity generated by RES and prescribes a fixed payment or price of electricity for the electricity suppliers.[E-wie-einfach] The first EEG was passed in 2000 and the currently valid last amendment to adjust the law to Germany's environmental and political goals is in force since January 2017 (EEG 2017) - this amendment is also valid for all biomass and biogas (electricity generating) facilities taken into operation from that date onward. [FNR, a] According to the first paragraph (§ 1) of the **EEG's goals and purposes** are four-fold. First, enabling a sustainable development in the interest of the climate and environment. Second, decreasing the costs of energy supply by including long-term external effects. Third, the preservation of fossil energy resources and fourth, supporting the development of technologies to generate electricity from renewable energies. [Umwelbundesamt, 2019]

The base period for the funding is 20 years. RES facilities with a capacity of up to 100 kW do have a guaranteed fixed financial compensation for the electricity fed into the grid. The compensation depends on the type of RES. Due to the technological developments and decreasing costs of RES facilities the subsidy period is limited. [Umwelbundesamt, 2019] **Flexibility premium** is a financial premium of the EEG2014 law. In order to promote the flexible operation of the RES capacities only half of the installed capacities (> 100 kW$_{el}$) is financially supported in combination with a financial premium of 40 EUR / kW$_{el}$ over 20 years for the total installed capacity.[FNR, a] For existing facilities that have not made claim of the flexibility premium of EEG2012 the premium stays the same, which means 130 EUR/year for each additionally flexibly provided additional kW$_{el}$ capacity for a maximum duration of 10 years. [Umwelbundesamt, 2019] Since August 2014, the total extent of the premium is limited to 1,350 MW$_{el}$. [FNR, a] In case of electricity generated by wind or photovoltaics the market premium starts at 750 kW$_{el}$, in case of the biomass-facilities at 150 kW$_{el}$ and above. [Umwelbundesamt, 2019] In 2012, 2014 and 2017 the framework conditions for the EEG-fundings of BG facilities was changed, so that until 2030 many of the installed BG-facilities will stop to receive the EEG funding - which leaves the BG operators with the central question on possible future pathways of their BG facilities[Daniel-Gromke et al., 2020]. By 2030 55% of all BG facilities and 66% of the installed capacity will not continue their operation[Daniel-Gromke et al., 2020, p.21]. Consequentially, the scientific officers see three different types of operational modes unfolding for the BG facilities: 1. Reduction of the substrate and thus less electricity production, 2. the flexibilisation of the BG and electricity production (see passage above) and/or 3. the switching to Bio-methane refinery.[Daniel-Gromke et al., 2020, p.21-22]

4.7.2 Subsidy programs for Solar Thermal in Germany

There have been Research and Development (R&D) programs for SDH by the federal government of Germany. Between 1995 and 2012, there were two of such programs that supported in total 11 solar thermal systems from the first development until their operation. These programs were accompanied by scientific monitoring programs to evaluate and proof economic and technical feasibility. [Lottner et al., 2000] Further, there are present funding programs on the federal as well as the state levels. This section will further explain the main subsidy and financial incentive schemes for large-scale STS and also SDH in Germany. It will not explain in detail federal state fundings on large-scale STS and SDH - such as the local SolnetBW program in Baden-Württemberg. [Landesanstalt Umwelt BaWü]

'Renewable energy - premium' No.271 by Germany's KfW-bank

The 'renewable energy - premium' no. 271 is a credit by the KfW bank, which is a German state-owned development bank and the third largest German bank by balance sheet. The renewable energy premium No. 271 aims at large-scale RES generation facilities and is basically an extension of the premium 270, that aims at smaller-scaled RES facilities. Premium No. 271 is basically a state-aided loan with an annual percentage rate of at least 1% (depends on the reliability of the borrower) and a maximum amount value of 25M EUR. Further, it is disposed of an allowance of the amortization up to 50%, which means that the liable party does not have to pay back the full amount - depending on the loan's conditions. Among the fundable technologies there are large-scale solar thermal systems, large biomass boilers, renewable district heating networks, large thermal energy storage systems, large-efficient heat-pumps, facilities of combined-heat-power and pipelines for unrefined bio-gas. The target group of of the premium No.271 are enterprises, private persons, farmers, municipalities, communes, cooperatives and contractors (utility companies). [KfW and BMWi, 2019]

Solarthermal funding by BAFA

The BAFA - Germany's Federal Office of Economics and Export Control ('Bundesamt für Wirtschaft und Ausfuhrkontrolle') also subsidizes the STS and SDH in a program called "Wärmenetze 4.0", equivalent to district heat networks 4.0, which is split up into four modules. The first funds a feasibility study with up to 600,000 €, the second, with up to 50% and a maximum of 15 M € installation costs are covered, the third funding-module funds up to 200,000 € for informing residents about a potential connection, and a fourth funding of up to 1 M € for academic institutions that accompany the project. BAFA [2020]

Summary from the theoretical framework (Chapter 4)

- Bioenergy-Villages' district heating are mainly (50%) supplied by non-space-efficient bioenergy fuels, which is leading to land-use conflicts and domestically limited resources in Germany.
- Biogas is often used to supply base load, and it is produced by mono-culture corn. EEG-funding on BG will therefore be stopped after 20 years (exceptions exist).
- Proposals exist to transform Bioenergy-Villages into Renewable-Energy-Villages.
- (Bio) Energy villages rely on different legal forms (eG, GmbH, GbR) to organize their heating system.
- The share of renewable energy supply for heating in Germany is 14.5%, 65.7% of which was biomass and 4.9% was Solar Thermal in 2019.
- In 2019, 19.3 M m^2 of solar collectors was installed in Germany, of which only 62,700 m^2 (44 MW_{th}) was SDH.
- In 2019, approximately 34 large-scale solar thermal systems (STS) existed in Germany - not all of them were SDH.
- Different studies estimate the technical potential for large-scale STS to be between 15-100 TWh_{th} and SDH is expected to have a significant share in it.
- Various SDH projects in Denmark, Canada and Germany exist and can serve as examples of Good Practices.
- Funding programs and subsidy schemes exist: namely *KfW-Kredit*, and BAFA's *Wärmenetze 4.0* for SDH. EEG-funding on electricity from BG is being phased out.

5 | Techno-economic potential of solar district heating

The following methodological framework was developed to answer the second sub-research question posed in the problem formulation 5.1:

How can the techno-economic potential for Solar District Heating in Bioenergy-Villages be assessed in terms of energy demand, area and price and what groups of Bioenergy-Village show to have a high potential for the application of alternative heat supply technologies?

The methodology used in this chapter is based on two interwoven methods M2.1 and M2.2 which are depicted below in Figure 5.1. The methods applied feed on the data-spread-sheet (Appendix 1 - external Excel-document) created on data-sheet information about demand (red, dotted line) and supply side (green dotted line) of the BED's district heating. After creating a data-spread-sheet of all BED three criteria sets were selected while taking an underlying theoretical framework (see 4) based on literature review (M1) into account. Consequently, there are three criteria that form groups of BED with a high potential. These are presented in 5.2 according to their installed BM and low BG capacity (green color) respectively the year of first installed BG capacity (red color). A third selection was, if SDH technology was applied in BED. Two BED were found that served as Good Practices as a basis for the analysis on the socio-organisational potential (see (M4) barrier analysis with semi-structured interviews - Chapter 7). In a separate analysis the BED's and pBED's internal techno-economical potential was determined (below in Figure 5.1 see 5.3). Therefor, the demand side information from the MCA's data-sheets was filtered based on two criteria (supply rate and heat demand equal) and the data subsequently processed to estimate the heat demand potential of the BED. Based on the heat demand the potentially required SDH collector field area was calculated equal to cover covering a solar fraction of 20% annually. Last, the price of equipping these BED with SDH installations was determined with a price regression-curve.

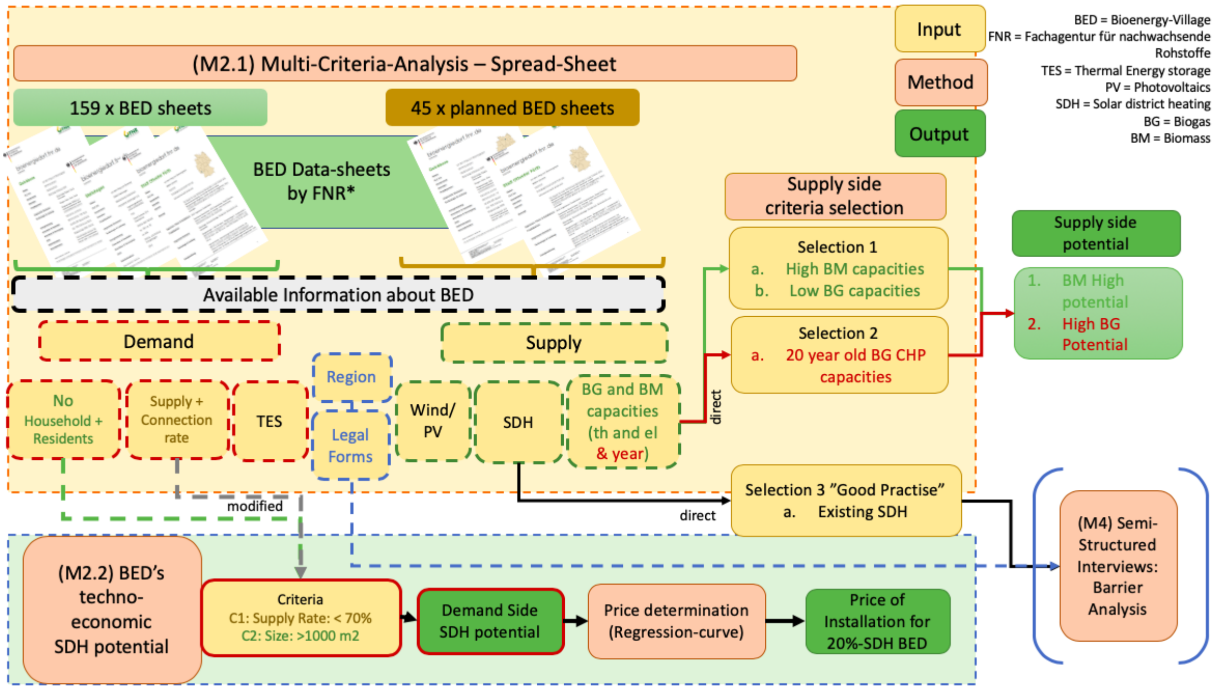

Figure 5.1: Methodology developed to assess the techno-economic demand side potential (M2.2) and to find groups of BED with a high supply side potential (M2.1). It includes methods of Multi-Criteria-Analysis (M2.1) and Techno-Economic demand potential based on a spread-sheet (Microsoft Excel)

5.1 Methodology: (M2.1) Multi-Criteria-analysis and (M2.2) Techno-Economic Potential

5.1.1 Introduction Multi-Criteria-analysis

Often decisions are being made based on intuitions, but when stakes are high, a Multi-Criteria-Analysis (MCA) can help to structure the problem and evaluate a situation. Usually, MCA is used to combine different results of analyses from different disciplines combining for instance social, sustainability, environmental and technological analyses - e.g. a transdisplinary study using MCA to evaluate energy scenarios for a planned Bioenergy-Village in Germany. Wilkens and Schmuck [2012] There are further examples how MCA are applied to RES planning, such as an analysis of energy system transformation pathways in Switzerland [Volkart et al., 2017] or used for RES integration in India [Vishnupriyan and Manoharan, 2018]. This range of applications show that the MCA is not used for a specific case, I therefor decided to make my own MCA to analyse the demand and supply-side potential based on the multi criteria found in the data-sheets of the FNR. I make use of the MCA in a different way since this analysis seeks to find well suited BED and pBED for the application of an alternative RES technology, but focusing SDH. The MCA shall aid me choosing the 'best' suited BED over many. After building a quantitative data-base presented in 5.1 of all BED, one or various criteria can be selected and also be weighted differently.

5.1.2 Data collection process, building a data base of BED

In order to find the BED with a high SDH potential, but also to determine the techno-economical potential, information on the demand and supply side of the BED was needed. The "agency for regrowing resources" ("*Fachagentur für nachwachsende Rohstoffe*") (FNR) In consequence, the FNR's homepage offers two different lists of BED. First, the list with officially (i) acknowledged BED (green in 5.1) with a bioenergy (biomass (BM) and bio-gas (BG)) fraction of at least 50% on the production side of both electricity and heating. Second, a type "waiting-list" of (ii) planned BED (brown in 5.1) that are have their heating energy system currently in development towards the FNR's definition (see also 4.1). For each BED and pBED exists a data-sheet of usually one to three pages comprising information on both the demand and supply side of each BED. After investigating the field of BED in detail, I concluded the FNR data-sheets constitute the best general data-source of the BED and pBED available. Hypothetically, only a case-to-case in-depth analysis or a new survey would create better data on the different BED. This was confirmed by a later interview with Dr. Hansen (see subsection 7.3.1 and ANNEX 2 (external document)). In a reviewing process of all 204 data-sheets I obtained relevant information and noted it in a spread-sheet (based on Microsoft Excel) that together with the criteria in Table 5.1 make up the basis for the the following analyses and results.

Quality and limitation of data-source

The **Period of data extraction** started in beginning February 2020 when the FNR-data base contained (i) 159 acknowledged BED and (ii) 45 planned BED. During the research process the number of acknowledged BED changed to 163 (May, 19th 2020). The **accuracy of data** of data is relatively good, since data-sheets of the FNR are clearly structured and were filled out by the specific proposed or applying project owner. Though the method of "data-sheet creation" changed during the time when the data-sheets were created according to a phone-call with Dr. Hansen. Hence, the accuracies of the described energy capacities and systems deviate from one data-sheet the other. Detailed information on annual load or production curves is not available in the data-sheets, thus no case-specific in-depth analysis of the sustainable energy systems can be conducted from the data-sheets. In order to do that one would need to get in touch with the energy managers of the respective BED. Some quantitative data described available in the data-sheets was deliberately not included into the Excel sheet. First,**(Fossil-fuel) backup boilers** were excluded from the data set, as this thesis aims at finding and supporting an approach of building a heating sector totally fuelled by a mix of bioenergy combined with other resources, since biomass has downsides such as the limited potential (see 4.2.2 and use of 1.

generation biomass (4.2.6. Second, the annual energy demand of the BED's DH systems was in the majority of cases not given, therefore I decided to make an estimate of the number of residents and households (see 5.1.4) where data was available in 154 out of 159 BED and 43 out of 45 pBED.

5.1.3 Supply side data - process of extraction, assumptions and extrapolations

This section presents how information on the supply side of the BED was extracted and which assumptions were made to complete the data-sheet (see Annex 1 (external Excel document)).

Supply side data extraction: Biomass and Biogas capacities

If the renewable energy share or the solar fraction of DH is to be increased, information on biomass (BM) and (b) biogas (BG) boiler capacities installed in each BED is required. In many BEDs there are 'combined heat and power' (CHP) units installed that generate electricity and heat, which is fed into the DH systems. The data on the BM and BG capacities of the CHP were excerpted under the following three rules. First, the information on the rated capacity "X" of a CHP plant (both BM or/and BG) was given, but it remained unclear it was electrical or thermal power, the rated capacity was saved as "X" in both electrical and thermal. Second, when only one electrical capacity of the CHP was given, the thermal value was determined to be 10% higher (technical advise by a colleague at Aalborg CSP). So for instance, if BG_{el} is 100 kW_{el}, the BG_{th} was concluded to be 110 kW_{th}. Third, if the thermal capacity was given, the electrical capacity was extrapolated. Furthermore, I distinguished the bioenergy facilities BM and BG since different economic, subsidy and technical framework conditions applying to the two biomass technologies. Generally, the **data availability** on capacities of BG and BM can be described good. Only our out of (i) 159 acknowledged BED and four out of (ii) 45 pBED had no quantitative data available on the capacities of the BG and BM facilities. The year of **start of bio-gas operation** was also extracted since in case of re-powering measures it was considered likely that old BG CHP plants or boilers could be replaced by or supplemented with a solar thermal system. Today, as described in subsection 4.2.6 BG is often used as a base-load in DH systems and further EEG-subsidies are likely stopped after 20 years (see 4.7.1).

Wind and photovoltaic capacities

Though, the focus of this paper is the implementation of STS into the BED's DH, the wind and photovoltaic (PV) capacities were also extracted from the paper. This was done, since the second analysis (see 6) further discusses the external RES potentials and seeks to analyse the residue biomass potential of each BED - which should be included into the planning and building district heating system 100% RES energy sector. Wind and PV electricity and availability need to be taken into consideration when acting upon the recommendation to couple the energy sectors (in this case with the electricity sector) via for instance heat-pumps or power-to-heat [Lund et al., 2014]. For BED with DH systems HP powered with abundant electricity from wind and/or PV at times of fluctuating electricity abundance is expected to play a decisive role in future DH systems.[Hadorn, 2010]

Installed solar thermal collector and thermal storage capacities

In order to find Good Practises among BED and pBED that already make use of SDH the information on if they have solar thermal collector (STC) fields installed were noted as well. In total, five BED projects seemed to comprise SDH. Further, the information on the thermal energy storage (TES) also were noted, since thermal storage is required if the solar fraction is to be lifted over 20% (see Good Practises4.6) and thus another group with a high SDH potential could be described.

5.1.4 Heat demand data: residents and households

This chapter seeks to give of how the data relevant to extrapolate the heat demand was obtained from the FNR'S data-sheets and how it was corrected.

Number of households and residents of the DH in BED

In order to extrapolate the heat demand I extracted the size of the DH system of each BED/pBED by obtaining total number of households and residents of the FNR data-sheets. 95.6% of the data-sheets had numbers of the residents on which basis the heat demand of the BED could be approximated. In some cases, additional information on heat demanding infrastructure such as town-halls, community centers, swimming halls etc. was available in the data-sheets, which was not obtained since I assumed that the consumer load of these demands varies strongly and cannot be generally quantified.

Supply rate and connection rate

The CR refers to the relative amount of households that have a physical connection to the DH system in regard to the total number of households available for connection within that BED or pBED. The SR refers to the amount of energy the system is able to deliver within a certain amount of time (usually it is referred to one year). 84.3% of the data-sheets provided data for the Connection Rate (CR) while only 10.1% for the Supply Rate (SR). The ratio between the SR and the CR has been determined to be at 1.26 by own calculation as 11 data-sets had information on SR and CR available, so that it could be used for a SR extrapolation from the CR values. Thus the SR is 26% higher than CR. Often the CR was not given or indicated directly in the FNR's data-sheets. With the help of the total (a) number of households available to the DH system and (b) the number of connected households a CR could be calculated by division:

$$CR = Households_{connected}/Households_{total,planned} \tag{5.1}$$

The physical connection rate CR for the BED is determined to be on average at 58.9% for BED and 42.4% for pBED. If the supply rate (SR) was available it was taken directly. If not, the CR was taken instead. If both values were not available the average CR of 58.9% (BED) respectively 42.2% (pBED) was assumed as SR. I met the assumption CR to be equal to SR considering the likelihood of a strong correlation between the CR and SR values (confirmed by Dr. Hansen from interview (i-1) and personal correspondence).

5.1.5 (M2.2) Techno-Economic demand side potential

This and the subsequent sections explain how the techno-economic heat demand potential based on the FNR data-sheets was assessed.

Heat demand calculation, interpolation and correction

In order to extrapolate and derive the annual energy heat demand (HD) for space and water heating of Germany's BED the energy usage is taken. In 2017, according to BMWI's data 447.8 Peta Joule energy were used for warm water and 2472.2 PJ for heating in Germany. At the same time, the country counted 41.3 Million (M) households and 82.9 M residents. Consequently, 2.01 persons per household on average. [BMWI] and the following annual heating demands:

1. Average household's heating demand in Germany: $E_{HH,BRD}$=19637.4 [kWh_{th}/a*household]
2. Average resident's heating demand in Germany: $E_{R,BRD}$= 9786.9 [kWh_{th}/a*person]

In order to determine the differing annual HD of each BED (HD_{pBED} and (HD_{pBED}) a correction based on the residents per household were included into the calculation of the HD of BED (see below 5.2) respectively pBED (see below 5.3). In Germany, on average 2.01 residents live in a household, whereas with the help of the data that in DH systems of the BED 2.65 residents (R_{BED}) per BED-household (HH_{BED}) were determined - respectively 2.40 residents (R_{pBED}) per pBED-household (HH_{BED}). Note: the heat demand calculated for the BED and pBED is only the heat demand of the residents and households and does not contain demand for additional buildings.

$$HD_{BED} = 1/2 * E_{HH,BRD} + 1/2 * (R_{BRD} * HH_{BED}/HH_{BRD} * R_{BED}) * E_{R,BRD} \tag{5.2}$$

$$HD_{pBED} = 1/2 * E_{HH,BRD} + 1/2 * (R_{BRD} * HH_{pBED}/HH_{BRD} * R_{pBED}) * E_{R,BRD} \quad (5.3)$$

5.1.6 Conversion to size of solar collector field

In order to extrapolate the size of the collector field a high-quality solar thermal collector by the Austrian producer *GREENoneTec* (GoT) was utilized that is being used for installations by the company *Aalborg CSP* in applications in DK and also for planned SDH projects in Germany. According to a test result this type of GoT collector yields on an annual basis 1244 kWh/m^2 in Würzburg, Germany (under standard test condition - Source: Certificate of performance [SOLAR KEYMARK]). The value for the annual yield was used and not adjusted (north or southwards), since it is highly probable that the main uncertainties are in the heat demand extrapolation (see above 5.1.5).

5.1.7 Assumptions for potential heating demand for Solar District Heating in BED

Two criteria were used in order to determine the total direct heating demand in Germany's BED. First, the SR should be 70% or lower, so that there is 30% of annual energy demand. The remaining third could be covered by a potential solar thermal system (STS) with a solar fraction of 20% - ergo covering 20% of the annual heat demand as other existing centrals in Germany and Denmark do (see Good Practices 4.6). Sizes beyond 20% are likely to require a Thermal Energy Storage (TES) in form of warm-water reservoirs that drive up the additional price of the SDH. Further, a solar fraction of below 20% was not chosen because the installation of a solar collector fields require certain minimum fixed costs (see next section 5.1.8). Also a SDH project becomes too expensive if only a small field for a small solar fraction is being installed (see below in 5.1.8). Further, a 20% solar fraction SDH system can after a successful operation be extended by adding solar collectors and a TES.

5.1.8 Determination of base capital price of Solar District Heating in BED

In order to determine the specific prices of the BED's and pBED's SDH with a solar fraction of 20% I used a base capital price system model based on a regression price curve obtained internally at Aalborg CSP. The base price includes 75 m of DH pipeline system that is suited for STS comprising up to 1500 panels (approx. 18,500 m^2), piping and pipework in the solar field, erecting and price of mounting systems, instruments in the solar field and programming, technical house with equipment (pumps, heat-exchanger, valves etc.), installation prices for mounting systems, solar collectors, material transportation, engineering work and overhead for the company. Excluded are the accumulation thermal storage (remember: solar fraction is set to 20%) and the integration price into the existing DH system. Consequently, the base price of the whole SDH installation is represented by the blue curve depicted in Figure 5.2 which is based on 19 different STC field sizes calculated with effective areas between 1,856 and 37,110 m^2 - respectively an equivalent to 150 to 3,000 GoT panels. (Note: thanks for providing information to my colleagues Lasse Kristiensen and Jes Donneborg)

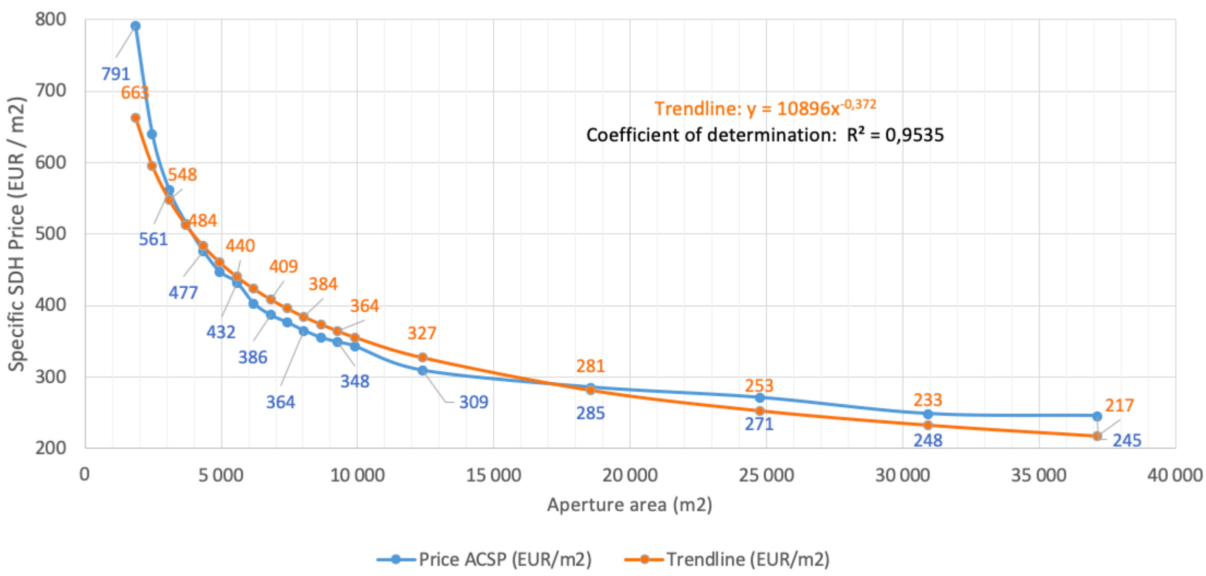

Figure 5.2: SDH system base capital price determination: Relation between specific SDH price (EUR/m^2) and effective aperture field area (m^2) based on internal information by Aalborg CSP)

The larger the solar collector field, the lower becomes the specific m^2-price of the whole SDH-installation because costs for planning, engineering, technical equipment (e.g. technical house). These investment costs need to be invested independent of the SDH's scale making up a certain base fixed price. The orange curve shows the corresponding regression trend-line of the blue curve that was approximated with the program Microsoft Excel and is represented by the following equation:

$$Price(EUR/m^2) = 10,896 * Area_{Aperture}(m^2)^{-0.372} \tag{5.4}$$

The function was subsequently used to determine the specific prices of the SDH systems mainly dependent on the different solar field sizes obtained for the BED and pBED. The coefficient of determination of the approximation is at R^2 = 0.954 and calculated by Microsoft Excel (orange in 5.2). Consequently, the trend-line approximation (orange) of the equation below is varying approx 4.5% of the original (blue) calculated values.

Criteria	**Condition**	**Description and reasoning for use**
C1. Supply Rate:	< 70 %	The remaining 30% of DH can be supplied by SDH with solar fraction of 20% without thermal storage, + 10% buffer for other RES (e.g. heat-pump)
C2. Collector field size = Solar Fraction of BED	> 1000 m^2	The minimum field size was set to 1000 m^2, since the SDH price declines progressively and the improbability of small SDH to compete (see Fig.5.2)
C3. BM capacity:	> 1500 kW$_{th}$	High BM capacity as BM can be (comparably easily) stored and the heat generation load shifted (to the wintertime)
C4. BG capacity:	< 500 kW$_{th}$	If only a small BG capacity is installed that, do not provide too much base-load so that other RES could be installed
C5. Age of BG capacity:	Year of installation	EEG-funding stops after 20 years (see 4.7.1, thus BG operators need to look alternative heat/electricity sources
C6. Solar Thermal System	Aperture area (in m^2)	Searching for Good Practices to understand how the first BED were equipped with SDH (see Chapter 7
C7.Organisational form of BED	Type of legal form	Differences in organisation, barrier analysis (Chapter 7) and legal forms (see 7.2.1)
C8. Regional distribution	Federal states	Local differences in decision-making, see also (Chapter 7)

Table 5.1: Criteria applied in the MCA supply side (C3, C4, C5) and demand side analysis (C1, C2) and barrier analysis (C6, C7, C8) - predetermined by FNR's data sheets

5.1.9 Multi-Criteria selection

Table 5.1 below shows the different criteria explained in the above section that were combined to show the BED's overall potential for SDH from the demand side (applying criteria C1 and C2) and the supply side (applying criteria C3,C4,C5). Further criteria, such as the regional distribution and types of organisation forms are used for the barrier analysis of the socio-organisational potential in Chapter 7.

5.2 Resulting supply side potentials based on Multi-Criteria-Analysis

The first section (see 5.2.1) gives an overview of (i.) the BG and BM capacities installed in the BED respectively pBED and shows the size of capacities installed on average. Further, the subsection 5.3 outlines the demand side of the different pBED and BED.

5.2.1 Biomass and Bio-gas capacities installed

The graph 5.3 depicts the average unit size on the supply side of BED (left side) and pBED (right side) fuelled by BM and BG. The overall impression is that the installed BG and BM capacities in the BED and pBED were scaled alike. The low electrical BM capacity indicates that BED have almost no CHP units installed that simultaneously produce electricity and heat. In the case of the BM facilities installed in BED (left graph) one can observe that out of the 102.7 MW_{th} only 8.9 MW_{el} also produce electricity. Further, the thermal capacity of BM is very similar in BED and pBED and on average at around 869 kW_{th} (BED) and at 842 kW_{th} (pBED). The ratio between thermal to electrical capacity in BM is lower in the case of pBED (right graph), so probably more CHP plants are installed

The comparably low absolute difference between the thermal and electrical capacity of BG (both graphs) indicate that BG is mostly burned in CHP plants - in both BED and pBED. These CHP plants fuelled with BG seem to supply base load heat into the DH system, which would make it hard to append such a system with another base load producing technology such as SDH.

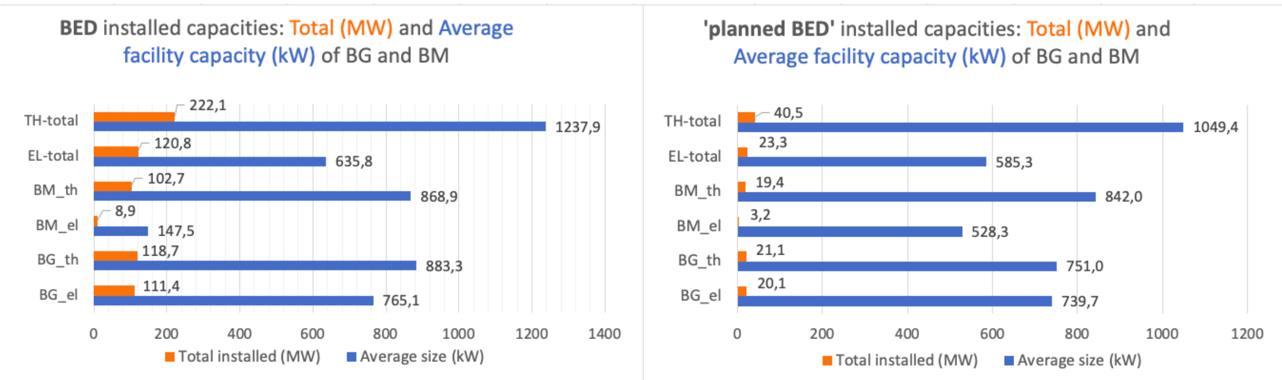

Figure 5.3: Biomass and biogas average sizes of capacities installed in BED and pBED

Figure 5.4 shows in two bar graphs: the top graph shows the total thermal BG and BM capacities installed while breaking them down into the individual capacity sizes. The bottom bar graph shows the total amount of BED respectively pBED in each of the the occurring capacity size groups. To give an example on how to read Figure 5.4: taking for instance the last bar graph "BM > 1,500kW" into regard: it means for the BED (green color) that in total 59.5 MW_{th} BM are scaled larger than 1.5 MW_{th} that are installed in 13 different BED. And two pBED (yellow) projects which have a total of 5.8 MW_{th} BM capacity installed.

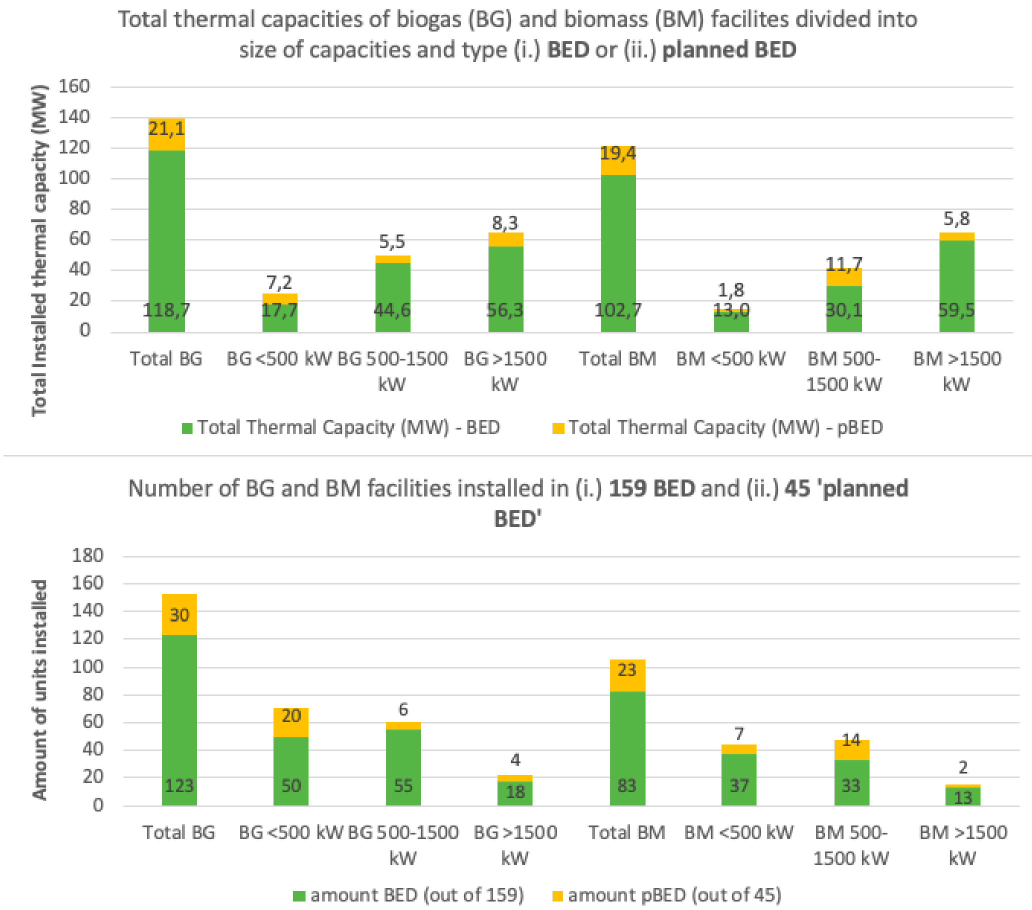

Figure 5.4: Total capacity (top graph) and total amount (bottom graph) of thermal biomass (BM, right side) and biogas (BG,left side) capacities installed in BED (green) and pBED (yellow) grouped according to their size

5.2.2 Year of first installation of bio-gas facilities

Figure 5.5 shows the years of the first installation of the BG facilities in the different pBED and BED. In total nine BG facilities have been installed until 2005. Note: only the available years of installation are depicted, which is 71 out of 159 (BED) and 14 out of 45 (pBED).

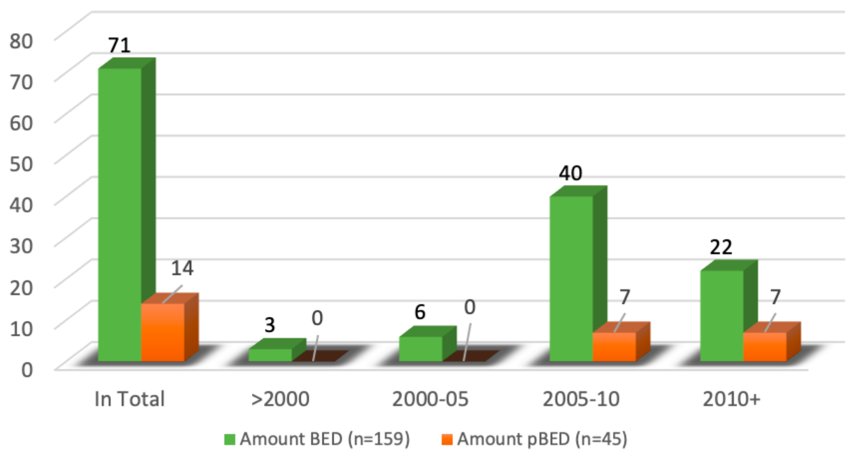

Figure 5.5: Year of installation of first biogas facility of the BED (green) and pBED (orange)

5.2.3 Good Practices: Bioenergy-Villages with solar district heating

Initially, the data-sheet indicated that there are five BED/pBED having larger-scale SDH installed which turned out to be only two within the research process. These two projects are subsequently portrayed. The first portrayed BED is **Mengsberg** located in the federal state of Hessen, with a DH system that has use heat demand of approx. 5 GWh_{th} annually. Since 2018 it has a net solar collector field of 2,755 m^2 and 224 panels that cover a solar fraction of 99 % in summer time and 17 % in winter time. A wood-chip-boiler covers 81 % of the annual supply.[Viessmann GmbH, 2020a] Second, the BED **Moosach** which is located in Bayern (BY) and has a running SDH since February, 2019 with a gross field area of 1,067 m^2 respectively 81 panels. Additionally, 1,450 kW_{th} of woodchip-boiler capacity is installed to cover the 2.3 GWh_{th} annually. Further, the DH system has a solar thermal energy storage with 100 m^3 storage capacity covering five to seven days of heat supply. [Viessmann GmbH, 2020b]

5.3 Resulting Heat Demand and Solar District Heating Potential of Bioenergy-Villages

The total Heating Demand (HD) of the BED and pBED is depicted in this chapter further explaining how it relates to the potential solar fraction. Further, the potential total aperture area of the solar thermal collector fields needed to supply the BEDs with this solar fraction and a subsequent distribution of the installation costs.

5.3.1 Resulting heat demand of Bioenergy-Villages

Figure 5.6 displays in two pie charts the absolute heating demand of the 159 BEDs (left graph) and the 45 pBEDs (right graph). Further, their respective potential share of the annual energy demand for the solar fraction (set to 20%) split up into the potential sizes of the installment that are ordered according to the annual energy demand.

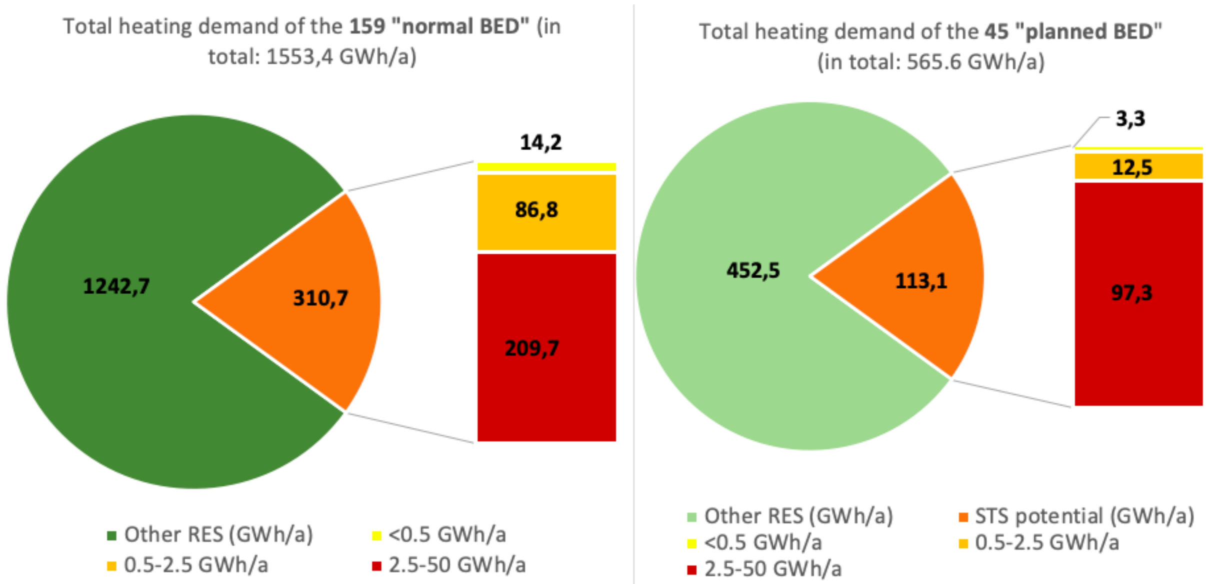

Figure 5.6: Total heating demand of BED (left) and pBED (right) with potential solar fraction (20%) broken down into the annual demands of the BED for STS or SDH

5.3.2 Aperture area required to supply BED demand with SDH

The graph 5.7 below displays BED projects that fall into the category of (i) having a SR of less than 70% and (ii) showing to have an annual heating demand that is higher than what equals an effective aperture area of 1000 (variable) m^2. Out of in total 104 BED and 35 pBED with a higher SR than 70% 56 BED and 18 pBED show to have the heating potential for a solar collector field area of 1000 m^2 and more. The collector fields larger than 1,000 m^2 make up 159,000 out of 181,000 m^2 for the BED and 78,000 out of 88,000 m^2 for the pBED.

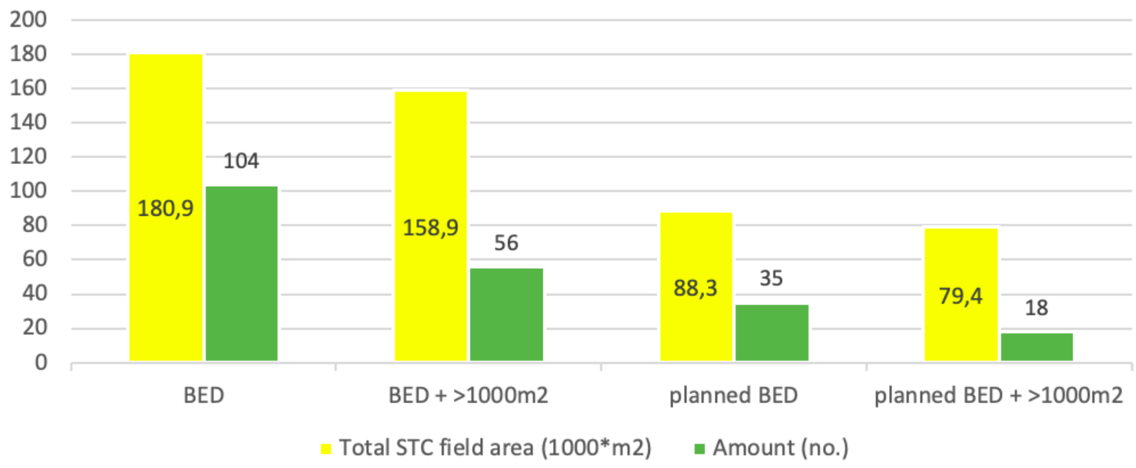

Figure 5.7: Potential size of effective solar thermal collector (STC) field area (yellow) of (i) BED and (ii) pBED and number of potential projects with < 70% supply rate

Figure 5.8 below depicts the distributions of the SDH effective collector field sizes of the 74 BED and pBED that show to have heat demand high enough so that their respective solar fraction of 20% equals at least 1000 m^2 effective collector area. The bulk of the BED is below 2,000 m^2, while 36 BED show to have a potential of between 2,000 and 5,000 m^2 collector field area. The average collector field area of the potential SDH for all 74 villages is 3,219 m^2 and in total added up 238,216 m^2. The smallest effective field area is 1013 m^2 (Lingelbach) and the largest 18,375 m^2 (Morbach).

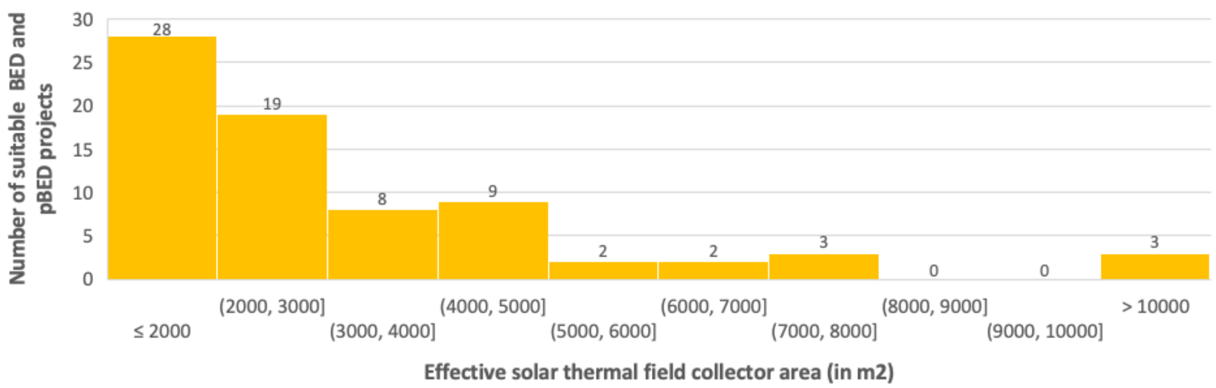

Figure 5.8: Distribution of potential solar thermal collector (STC) field areas of the 74 BED and pBED applying C1, C2 from Table 5.1 - ergo those with 1,000 m^2 applying a solar fraction of 20% to the BED's heat demand.

5.4 Price for equipping potential BED with Solar District Heating

The Figure 5.9 below depicts two graphs showing the distributions of the total (right graph) and m^2-specific (left graph) installation price of the SDH according to a price determination conducted according to section 5.1.8. The price of the average SDH installation in the BED and pBED is at 1.64 M € with an average specific price of 607 €/m^2 and 3,219 m^2 aperture area.

The price range is from the smallest project with 1,013 m^2, a specific-price of 830 €/m^2 and thus approx 840,000 € as a total base capitcal prices to the largest SDH field would comprise 18,375 m^2 (Moorbach), a specific price of 282 €/m^2 and a total base capital price of 5.19 M€. The 27 BED projects with a specific price <6 50 €/m^2 range between 1,013 and 1,883 m^2.

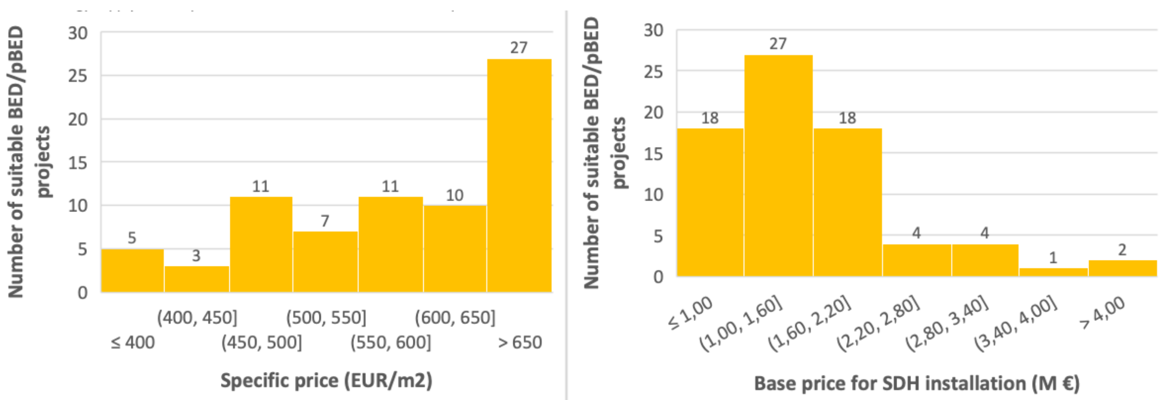

Figure 5.9: Distribution of the specific (left) and total (right) base capital prices of SDH installation in the 74 suitable BED with more than 1,000 m^2 (C2) and 70% supply rate assuming a solar fraction of 20% (C1).

In total there are 18 projects where the installation would cost less than 1 M € and only three BED where a the SDH is over 3 M €. If the whole area of 238216 m^2 of all suited 74 BED and pBED would be equipped with SDH the base capital price is at 121 M €. Note: all prices do have a deviation of at least +/- 4.5% determination via the regression curve (see section 5.2)

5.5 Summary, limitations and outlook

The table below summarizes and starts to discuss and concludes the data presented in the above sections.

Summary and conclusions from chapter 5 further discussed in chapter 8)

- Generally, there are not many BM-CHP and more BM-boilers installed in the BED-group, which bodes well for SDH since no EEG-funding can run out.
- pBED have a comparatively higher share of BM-CHP (combined electricity and heat) installed than BED (probably due to EEG-funding), thus positioning a bit worse for SDH as they are dependent from the electricity sector.
- In total, a group of 15 BED have thermal BM capacities of more than 1,500 kW_{th}, which presents a possible opportunity to combine with SDH.
- A second group is made up by 9 BED have BG CHP-facilities installed before 2005 in the 159 BED, which might need to be replaced soon after 20 years of EEG-funding. (See 4.7.1)
- Potential demand for SDH is at 310.7 GWh_{th}/a for all 159 BED and 113.1 GWh_{th}/a for 45 pBED, which is equivalent to around 180,900 m^2 and 88,300 m^2 respectively of solar field area that have a supply rate of over 70%.
- Applying additionally criteria of (C1) solar fraction of 20% (no TES) and (C2) minimum of 1,000 m^2 summed up around 238,000 m^2 (total) of effective aperture area could be installed.
- The non-subsidized capital price of SDH is 607 €/m^2, so installing SDH in all BED and pBED with criteria (C1,C2) would have a base capital price of approximately 121 M €.
- 8 BEDs and pBEDs show to have specific installation prices of less than 450 €/m^2 total capital prices of more than 2.6 M € - due to the comparably large sizes of the solar fields.

Conducting an overall multi-criteria meta-analysis of the BED's techno-economic potential was accompanied by the **limitations** of the method due to gaps in the information of the data-sheets by the FNR. On one hand, the accuracy of the data on the BED created the opportunity to conduct this type of analysis. On the other hand, as time-series, peak-loads, and base-loads data were not available, no in-depth analyses could not be conducted. The same applies to the extrapolation of the DH's heat demand for the BED. Assumptions based on the number of households and residents of each village needed to be made to determine their heat demand. Additionally, the FNR's data sheets are from 2017-2019 so that the present situation could not be 100% depicted.

A potential **outlook** from meta-analysis is that now, after the first peak of the COVID-19 pandemic, the specific groups of BED based on the criteria described are known. Developing a computer model of the heat energy system should be conducted now in order to demonstrate that SDH could be a viable option. Subsequently, I would recommend sharing this with the top "high potential" (according to criteria C1 to C5 in Table 5.1) BED and pBED for further in-depths analyses.

6 | Analysis of the external resource potential of biomass residues of BED

The first analysis aimed at the internal techno-economical potential that depends on both the internal parameters of the BED respectively pBED, but also to provide a tool that aids to choose specific BED due to their characteristics on the supply side (see 5.3). However, the technological potential of the individual RES and their share in the supply of the BED depends on outside - or external - availability of renewable energy sources (RES). The availability of different RES varies strongly with the location of the BED. To give two examples: a BED in the northern German state of Schleswig-Holstein (SH) with abundant wind electricity can be estimated to have a higher potential for heat-pumps or power-to-heat. Another BED located in southern state of Bavaria (BY) has probably a higher potential of solar radiation and thus PV electricity, that can also be used for heat-pumps. There is a series of RES that represents and affects the external technological resource potential based on the different energy conversion technologies. Each rural village and thus BED possibly has its own specific generating potential from an individual RES-mix - whatsoever this chapter focuses on analyzing the bioenergy potential as an exemplified, and biggest external energy potential supplying BED and thus assumingly directly impacting the utilization of SDH and of course the whole energy-mix of each BED. The section below depicts the different RES external potentials relevant for BED while outlining the choice of bioenergy- respectively biomass as central subject of the analysis. Overall, this chapter seeks to answer the following 3^{rd} sub research question:

To what extent can other external technological renewable resource potentials be considered and how can their influence on the application of the usage of solar thermal systems in the Bioenergy-Villages' heating sector be quantified?

6.1 Different potentials of renewable energy

In order to transform an existing 'Bioenergy-village concept' towards a 'Renewable-energy-village-concept' - as some scholars argue [Jenssen et al., 2014] - it is necessary to understand the existent RES technologies and their immediate adjacent potential to contribute directly to the electricity or heating generation. The list below enumerates RES that have potential effects on the supply of the heating system of villages via the technologies of heat-pumps, power-to-heat, and solar-thermal. I consider it of capital importance to understand the context of each BED, by understanding primarily the unique potential of bioenergy that supplies, today, the lion share of the BED's energy production - compare BED's definition section 4.1.

1. Bio-energy potentials of biogas and biomass in the region of the BED.
2. Electricity potential of other RES-capacities, most importantly wind and photovoltaics: "wind-map" and "radiation-map"
3. Solar Thermal Potential map that depends directly on two parameters: (a) Global Horizontal Irradiation (GHI) and (b) the ambient temperature
4. Geothermal energy availability.
5. Space availability: site for solar thermal collector field (can also be allocated as internal characteristics)

6.1.1 Why to focus on biomass?

As described in subsection 4.2.3 the potential of biomass (BMP) is almost completely utilized in Germany. In consequence, if the solar fraction - or also other renewable energy fractions - of the energy production in the BED and pBED is to be increased, it is crucial to understand the specific remaining biomass potential of each BED in order to know where the implementation of an alternative RES seems most urgent. The potentials of other RES also depend on external conditions, such as the distribution of solar radiation (via the Global Solar Atlas [ESMAP et al., 2019]), wind velocities (Global Wind Atlas [DTU Wind Energy and World Bank Group, 2018] and ambient temperatures [Deutscher Wetterdienst, 2020]). All these specific values and data that are comparably easy to obtain. Wind distribution depicts the potential distribution for electricity generation that can be transformed to heat via a heat-pump and vary strongly from north to south. The distribution of the solar radiation combined with the ambient temperature is needed to estimate the specific potential for every BED location for photovoltaic, but also solar thermal technology. In contrast, there are two potentials that are not easy to estimate, which are geothermal energy and bioenergy potential. In Germany there are three areas of major hydrothermal resources that are: the North German Basin, the southern German molasse basin and the upper Rhein Graben. [Weber et al., 2013] This heating energy resource is also becoming more relevant and might play a role in larger DH systems and should therefore be kept in mind, when planning the energy system of larger BED. In contrast, also the potential of bioenergy for specific location or radius compared to data on wind, sun and ambient temperature. There are different estimates for the biomass potential of whole districts (NUTS3-level) on a European level. [Hamelin et al., 2019] [Peta4]. Two online tools exist that open-source and GIS-based, but - as to my understanding - do not allow calculate residual, second-generation biomass for a radius around a specific location. First, the EU Hotmaps project which is a planning toolbox to map heating and cooling sources to support planners to develop energy strategies also on basis of RES and CO2-Emission [Hotmaps Project]. Second, the "Heat Roadmap Europe" project which also merges heat demand potentials with heat resources in order synchronize the potentials these. [Peta4] The next chapter explains the method that was developed in order to quantify and evaluate the BED'S biomass residue energy potential (REP) , that could - for instance - influence a MCA.

6.2 Method to determine the BED-specific biomass residue potential

Figure 6.1 depicts the setup of the (M3) methodology used. In order to determine the Biomass Potential (BMP) of each specific BED respectively pBED a methodology was developed based on the software Q-GIS (respectively PostGIS). Both softwares work with the *Geographic Information System* (GIS) and are meant for viewing, editing and analyzing geo-spatial data. The basis of GIS, input data and source are further explained in the following chapter 6.2.1.

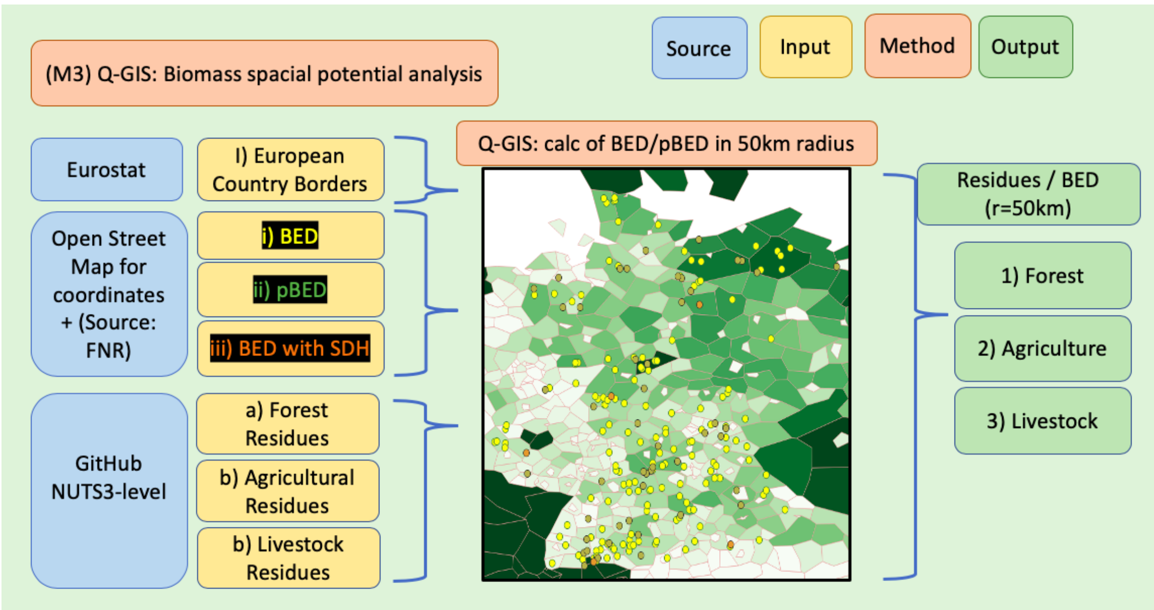

Figure 6.1: Methodology of calculating an approximation of the annual energy residue potential of biomass (a. forest, b. agricultural and c. livestock) in an 50km radius for each i) BED, ii), (iii) pBED (BED with SDH) using GIS-software

The underlying idea of the methodology depicted in Figure 6.1 is to combine the locations (coordinates) of each BED with data on biomass(es) of a certain radius (set to 50 km) around each BED in order to create indicative values about which BEDs apt for the application of alternative RES technology depending on their biomass availabilities. To conduct this analysis a three-fold input source (blue color) is required that provides input data (orange) which were displayed in a map in Q-GIS as shown in Figure 6.1. NOTE: the map shows three 'types' of BED, since during the research process a third type BED type of BED with BM and SDH was introduced.

6.2.1 Fundamentals of GIS, input and sources of data

The program Q-GIS needs information about the Coordinate Reference System, that describes the combined projection at a datum of a coordinate system. A projection refers to the transformation of a specific position on the surface of planet Earth into the position in Cartesian coordinates. The geodetic model takes the ellipsoid shape of Earth into account. Basically, there are two representations of data sets I have worked with - (i) the vector and (ii) the raster system. Vector data consists of points, lines and polygons that are discrete objects, which means that forms such as the districts ("*Kreise*") of Germany can be depicted - for instance biomass data. Whereas, the raster format is representing a varying surface in continuously-field perspective - e.g. wind, temperature and solar data. [Longley and Maguire, 2001] [Support by Anna Lea Eggart - Student of Cities and Sustainability M.Sc.]

The following Table 6.1 presents a list of data-sets used to create the map that constitutes the base for further calculations of the residue BMP. Furthermore, it includes their format (raster or vector layers) and the source organisation and website from which the data was obtained.

Type of Data set	Format	Source
(I) Eurostat countries	Vector polygons	[Eurostat, 2019]
(a) Forest residues	Vector polygons	[Pezzutto et al., 2018]
(b)Agricultural residues	Vector polygons	[Pezzutto et al., 2018]
(c) Landstock residues	Vector polygons	[Pezzutto et al., 2018]
(i) & (iii) Location of the BED and BED with SDH	Vector points	List-1:"*Bioenergiedörfer*" [FNR, b]
(ii) Location of the planned BED	Vector points	List-2: 'on the way to "*Bioenergiedorf*"' [FNR, b]

Table 6.1: Overview of the different data-sets used for the analysis of the BEDs' biomass residues potential

The locations of the BED and pBED were obtained via OpenStreetMaps where all villages were put in manually into a map from which the coordinates could be retrieved that were then inserted into Q-GIS.

6.2.2 Biomass data source description

The data of the biomass was obtained from the EU Hotmaps Project [Pezzutto et al., 2018] in which scholars estimated the different types of biomasses based type-specific methodologies [Garegnani et al.] due to different availabilities of data. The subsequent data-sources are all based on the "Nomenclature of Territorial Units for Statistics" (NUTS - from french "*Nomenclature des unités territoriales statistiques*"). Subsequently, the origin of the data of the three biomass-types is shortly depicted. First, the **forest residues** is based on the project Corine Land Cover and is spatialized data on a NUTS3-level resolution, containing information on broad-leaved, coniferous, mixed forests, natural grass lands, moors and heath-lands, "sclerophyllous" (hard leaves, short internodes) vegetation and transitional woodland shrub. Second, the **agricultural residues** is obtained by the LUCAS framework [Eurostat] that surveyed the statistics of land use and covered the EU28 territory. It is organized in a grid of geo-referenced points of the EU28 with statistics on a land use/cover class. The listed classes of each type of biomass residues was crossed with the vector at national-state-level (NUTS0) and district-level (NUTS3) from which the relative share or ration between NUTS3 and NUTS0 for each class was obtained. This value again was multiplied with the energy potential of each type of biomass at national level. Agricultural biomass includes: cereal straw, grain maize stover, rice straw, sugar beet, rape and sunflower stubble, citrus pruning, olive pruning and pits and vineyard pruning. Third, **livestock residues** were estimated based on the EUROSTAT data base statistics on livestock head counts on NUTS2-level (38 administrative regions in Germany [EUROSTAT, 2018]) and national-level (NUTS0) and thereafter approximated by combining it with the number of manure storage facilities at NUTS3-level.

Accordingly the processing of the residues data of (a) forest, (b) agriculture and (c) livestock within a radius of 50 km around the different types was eventually conducted in PostGIS as displayed and explained in the scheme in Figure 6.1 above a detailed description can be found in Appendix A.

6.3 Resulting distribution biomass residues potentials of the German Bioenergy-Villages

This chapter presents in three subsections the statistical distribution of the resulting BED-specific annual residue energy potentials (REP) in an radius of 50 km of each BED according to the calculation presented above. The idea behind the presentation of the statistical distribution of the calculated and aggregated value is to show an overview of the data. The following numbers depict are the theoretical - not the technical or feasible - potentials of biomass residues. (Please, see also the potential distinction and definition section 4.2.2). NOTE: there are approx. 204 individual values for each biomass residual energy potential behind that can be attributed to the specific BED and can only be traced back manually (due to "*Umlaut*-errors" in GIS).

6.3.1 Forest residual potentials

The average annual forest residual energy potential (REP) of the BED and pBED is 8.60 Peta Joule (PJ) (equals 2389 MWh_{th}- the distribution of the forest REP is depicted in Figure 6.2. The minimum forest REP is BED Stedesand (in SH, among the two most northern BED) with 1.30 PJ/year and the maximum BED Schmallenberg (in NRW) with 13.73 PJ/year - which also depicts the overall bandwidth of annual forest residual potentials presenting a ratio of about 10 between the highest and the lowest REP. In total, 23 BED are among the lowest 30% (equals 1.3-5.5 PJ/year) potentials of forest residues. Whereas, about one quarter of the BED has a forest REP in the 10% around the average value.

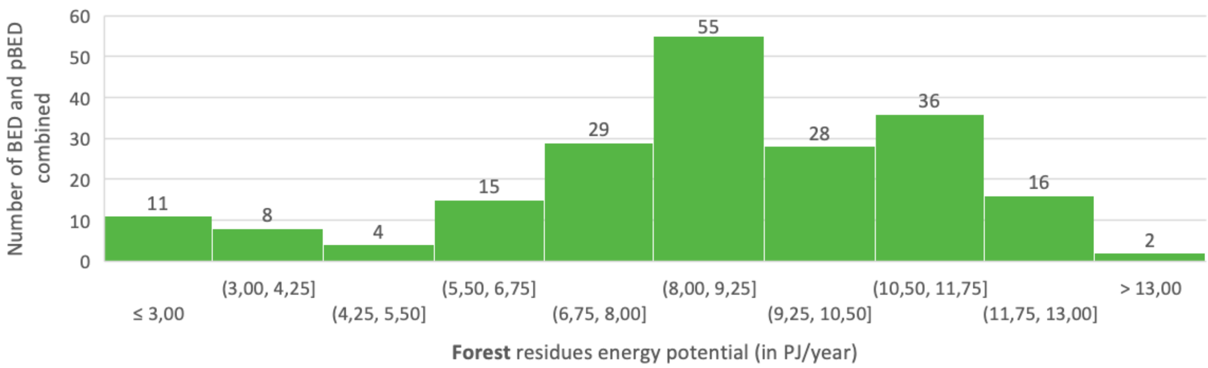

Figure 6.2: Statistical distribution of aggregated energy potential (PJ/year) of **forest** residues of all BED and pBED

6.3.2 Agricultural residual potential

The average annual agricultural residual potential of all BED and pBED combined is at 2.47 PJ (equals 686 MWh) which is depicted in 6.3. They range between BED Hägelberg (in BW) with a the minimum 0.34 PJ/year and BED Schkölen (in TH) with 5.71 PJ/year - with a ration of almost 17 between maximum and minimum. Almost 50% of all aggregated energy values (91 out of 205) are accumulated around the average value (2.47 PJ) in the range of 2.0 to 3.0 PJ/year. 59 are shown to have values in the lowest 30% between 0.34 and 2.00 PJ/year. There are only three REP higher than 5.0 PJ/year that are also representing the upper 20% of the range and only 12 form the group of the upper 30% comprising more than 4.0 PJ.

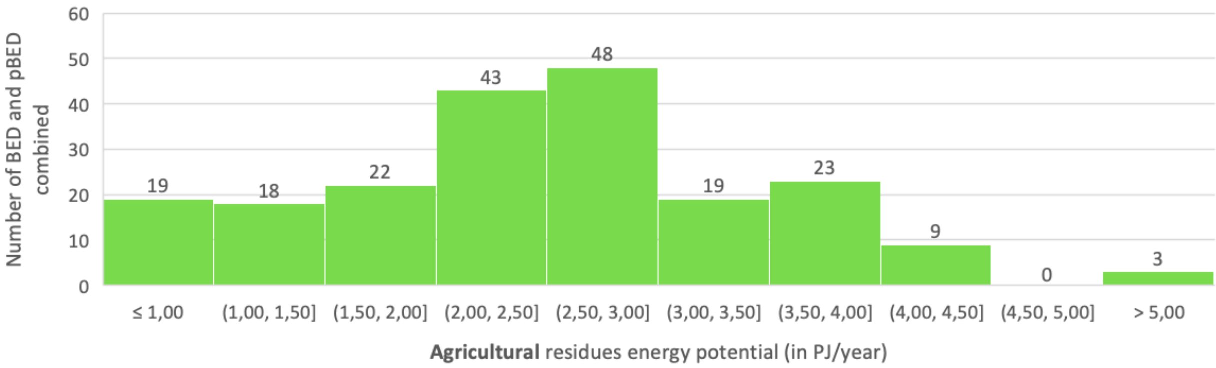

Figure 6.3: Statistical distribution of aggregated energy potential (PJ/year) of **agricultural** residues of BED and pBED combined

6.3.3 Livestock residual potential

The average annual agricultural residual potential of all BED and pBED combined is at 2.09 PJ (equals 582 MWh) which is illustrated in 6.4. The range is between BED Grambow (in MV) with a the minimum 0.50 PJ/year and BED Ocholt (in NI) with 6.33 PJ/year - with a ration of about 12 between maximum and minimum. More than half (118 out of 205) are accumulated in the lowest 30% of the range between 0.5 and 2.0 PJ/year, while only 7 values represent the highest annual energy values from the bandwidth. The highest 10% comprises six BED, with higher REP than 6 PJ/year are all from north-western Germany, where animal-industry is located.

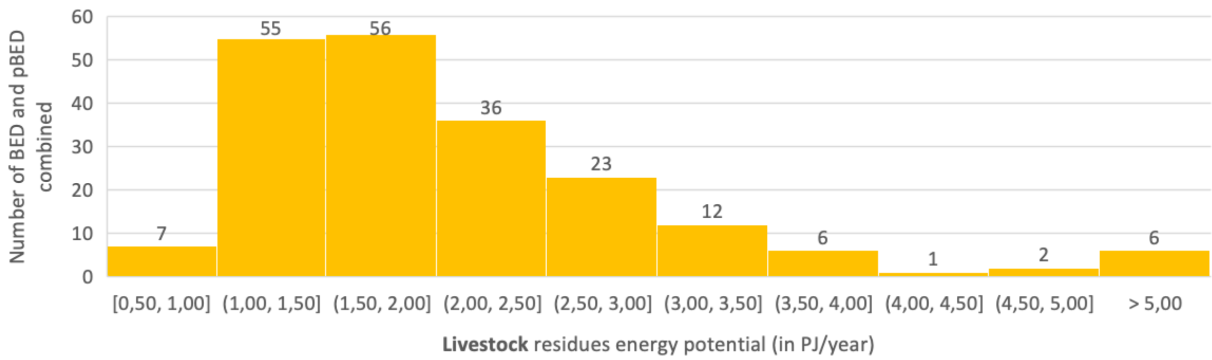

Figure 6.4: Statistical distribution of aggregated energy potential (PJ/year) of **livestock** residues of BED and pBED combined

6.4 Summary, limitations and outlook

Summary and concluding remarks from chapter 6 further discussed in chapter 8

- The REP values must be seen as indicators showing the theoretical annual potential of each region and not as absolute values. The average REP are forest at 8.60 PJ (ranging from 1.3 to 13.73 PJ/a), agriculture: 2.47 PJ (ranging from 0.34 to 5.71 PJ/a) and livestock: 2.09 PJ (ranging from 0.5 to 6.33 PJ/a)
- It is assumed that solid forest and agriculture residues (e.g. straw residues) are potentially utilized in biomass-boilers and agricultural (e.g. straw), whereas liquid livestock (e.g. manure) and agriculture (e.g.corn) REP are likely fermented and converted into biogas.
- 23 BED are among the bottom 30% group of forest REPs
- 45 BED/pBED (22.1%) are among the bottom 30% of agriculture REP, which might influence the biomass boiler heat generation and thus bode especially well for SDH and other RES.
- 7 of the livestock REP are among the lowest 10% on the bandwidth. BED with a biogas facility and a low livestock are well positioned for the implementation of alternative RES such as SDH.
- The livestock REP is generally lower than REP of forest and agriculture and for the individual BEDs. With the help of the livestock REP, a balance between biogas and biomass heat supply can be achieved, complemented by other RES heating technologies such as SDH.

Possible **limitations** of this method are: first, the spacial resolution of the biomass residues are on a NUTS3 level that is founded on different data bases and partial approximations. This becomes especially important when the REP of small radii are analyzed. Second, the database does not account for energy conservation. Consequentially, the values need to be "considered as indicators, rather than absolute figures" [Garegnani et al.]. These are the theoretical maximum potentials and cannot be compared directly with the heat demand of the households. The REP values of 8.60 PJ (forest), 2.47 PJ (agriculture) and 2.09 PJ (livestock) seem high. One must consider that only a fraction of these indicating REP values covers the biomass demand of (a) the region within a radius of 50 km where multiple other BED/pBED and/or more rural villages are located and the REP should contribute to (b) all three energy sectors - not only heating. Third, the radius of 50 km is, logically, a variable. The multiple radii of the roughly 200 BED overlap with each other so that the reach of the REP is double-counted and aggregated multiple times. As such, if all REP values are summed up, the result is higher than the unused potential presented in 4.2

An identified area for **future research** is for the GIS method proposed in this paper to be further developed so that adjacent BED are taken into account by avoiding the double-counting of the REP multiple times. An accounting method must be developed. One possible solution would be for the REP of adjacent BED to be aggregated into a "Bioenergy-Region". Another would be for this region to be split up according to each BED's respective percentage share in land areas. Another area for further development is for the REP values to be put into context with the other RES potentials by calculating the individual RES mix potential of each BED and pBED. This does also account for other (German/European) villages, bearing the whole heating transition in mind. A final step for further development is for the BED or village specific REP potential to be merged with the technological indicators of the MCA analysis. One could, for instance, filter for low agriculture and forest REP values while also identifying installed BM facilities that need to be replaced or at least supported by a potential SDH system.

7 | Socio-organisational barrier analysis

This third analysis emerged from a part of the results of the Multi-Criteria-Analysis (MCA) that showed not only the techno-economic potential as depicted in chapter 5, and the external theoretical RES potential (chapter 6. BED are socio-technological systems with a case-to-case specific "nexus of rules, social capital and cooperation" [Von Bock Und Polach et al., 2015, p.1]. Pre-assumingly, rather qualitative factors that are potentially informed by quantitative factors (as explained below) impose an influence on the decision-making processes of BED. Understanding the socio-organisational implications on the decisions of heat supply technology could enhance the BED's transition towards renewable energy villages - as proposed by [Jenssen et al., 2014]). This chapter seeks to respond and tackle the following fourth sub-research question:

To what degree do socio-organisational and techno-economic barriers hinder the implementation of alternative RES technology to supply Bioenergy-Villages' district heating and what are potential approaches to overcome them?

On basis of the data-sheet, out of which the MCA analysis (chapter 5 emerged, quantitative data could be obtained: namely, the BED's spatial distribution in Germany's states and also the different organisational respectively legal forms. The quantitative results of the MCA are shown in the next section 7.2, thereafter the methodological approach of the semi-structured interviews is explained in section 7.3 and subsequently the analytical results extracted from interview shown in section 7.4. However, the following section 7.1 seeks to contextualise and delimit the methodologically approach of interviews of related studies in the research field of SDH and BED.

7.1 Scientific contextualization: choosing interview as method

First, the scientific publications - according to my literature research - on implementation barriers of SDH, that are beyond analysis of the technological barriers, are comparably rare. This section seeks to depict the scientific framework of SDH and/or STS in the context of BED respectively other community energy projects in Germany.

A market analysis by trend:research/Leuphana and Lüneburg [2013] inteded to define citizen energy projects and their market share. For STS the results of this study were that private citizen energy facilities were largely dominating the usage of STS in Germany. Between 2007 and 2009 approx. 98% (equalling to 83 facilities) of all STS were installed in private households - the same accounted for STS collector area (the examination included large-scale STS facilities). The low significance of commercial facilities in the German market correlated with the examination of the low total amount of funding-applications for (large and small scaled) STS. In 2011, the "market-incentive-program" KfW credit (see also 4.7) for commercial STS represented just 3% (equivalent to 83 facilities) of the total funding-applications received by the MAP-KfW program. [trend:research/Leuphana and Lüneburg, 2013]

Another interdisciplinary study - from the field between energy engineering and sustainable development - focused on different RES scenarios for the specific Bioenergy-region *Ludwigsfelde* (the concept equals an accumulation of BED). Here the two scholars evaluate the tool of a multi-criteria decision analysis that applies social and sustainability criteria to evaluate the local impact of different RE scenarios on the region *Ludwigsfelde* in order to enhance the decision-making process. [Wilkens and Schmuck, 2012] Further, the paper of Von Bock Und Polach et al. [2015] investigates the nexus of rules, social capital and cooperation of bioenergy in socio-technical systems - namely of two BEDs in the state of Brandenburg. The scholars try to scrutinize how social capital (such as trust and cooperation) impacts the (in-)formal rules and thus has positive and/or negative effects on the decision-making-processes. They find that only a minority of energy research projects make use of socio-organisational analyses and deduce that decision-making, though collective action based on transparency and trust are key for the development of a community renewable energy system. [Von Bock Und Polach et al., 2015] Another study from Basque-Turkish universities analyzes German bottom-up the energy-village movement and proves them to be not only socially and environmentally, but also economically feasible. This is supported by the claim that bottom-up initiatives contribute to energy sustainability goals with a top-down state-driven plan (incentives, funding etc.) if combined well. Akizu et al. [2018] Content wise the probably most relevant, though not a peer-reviewed paper or official study, is a survey conducted by the private consultancy enterprises *Solites* and the *Steinbeis Forschungsinstitut* on the market players on trendsetting concepts for SDH in German communes. The goal of the research was to understand the "identification of the chances and possibilities to introduce more complex, and larger [solar thermal] systems" [Geiger, 2019], targeting at higher solar fractions beyond 15-20% and reaching 30-50%. The researcher sent a survey with 12 questions to in total 12 interviewees in the positions of planners, operators, project managers or community representatives. Subsequently, the most important results of the non-representative survey Geiger [2019] are summarized below:

1. **Social reservation for STS:** the interviewees mentioned that demand is covered by competing biomass/gas facilities. Further, they mentioned doubt that an economic feasible operation is possible (mainly due to thermal energy storage tank costs). Further, it was stated that hardly any excursion goals to large-scale SDH with high solar fractions

exist.

2. Circumstances that would create higher investment or heat price feasible: political incentives, higher funding, acceptance by citizens.

3. The biggest **constraints of implementation** of STS: Land area requirements, the heat price and investment costs.

4. Conditions needed to be created or changed that would increase the solar fraction: Education of citizens, political incentives, price for areas for STS.

5. **Solutions proposed** by the interviewees: energy cooperatives involvement, determining a minimum heat demand, base-load from STS or CHP, further one needs a prioritisation of STS in the planning progress and a privilege in the access to outskirt areas.

6. The **demands** from the survey: more education and seminars on SDH, presentation of pilot-projects, combinations with other concepts or/and technologies such as "agrothermal [combination of agriculture and solar-thermal field]systems" [Geiger, 2019, p.14] and heat pumps.

The survey contains elements, questions, but also solutions of the barriers' analysis in form of guided interviews that I conducted - though it differs from the analytical direction of my analysis, that is about comprehending the overall structural hindrances of the SDH not being applied in Germany. My approach differs methodologically by being a semi-structured interview of experts and professionals that work with SDH and BED on a daily basis - not a survey with the professionals directly from the BED. Thus the interviews might potentially complement the knowledge on socio-organisational barriers from a broader, rather meta-perspective on the BED.

7.2 Result from MCA: Distribution in legal forms and regions of Bio-Energy-Villages

This section depicts the two distributions: the first one is the regional distribution of BED and pBED and the second one is about the legal forms of BED and pBED. These distributions partially result of the MCA (see section 5.1. The subsequent interviews seek to analyze the barriers aiming at generating new knowledge on how the regional distribution (below 7.2.2) and different legal forms (below 7.2.1 as results from the MCA interact with decision-making and financial barriers. Further, if and how other barriers constraint today in 2020 inform the development of the large-scale use of STS in DH and consequently SDH in Germany.

7.2.1 Distribution of legal forms of BED and pBED

During the research process it became clear that the BEDs and pBEDs and their subsequent energy corporations organize the production and distribution in different legal forms that have inherently different legal conditions and decision-making processes. In total, there are several legal forms and usually each BED has its own, often, unique way or combination how it organizes itself legally. This means that usually the interaction of the different institutions within the BED based on different legal forms of each BED/pBED is designed in a unique way up to a certain degree. If there there were several legal forms of different participating institutions intended to always extract the over-arching type of organisational or legal form found in each BED. Figure 7.1 depicts the distribution of the legal forms found in BED respectively pBED.

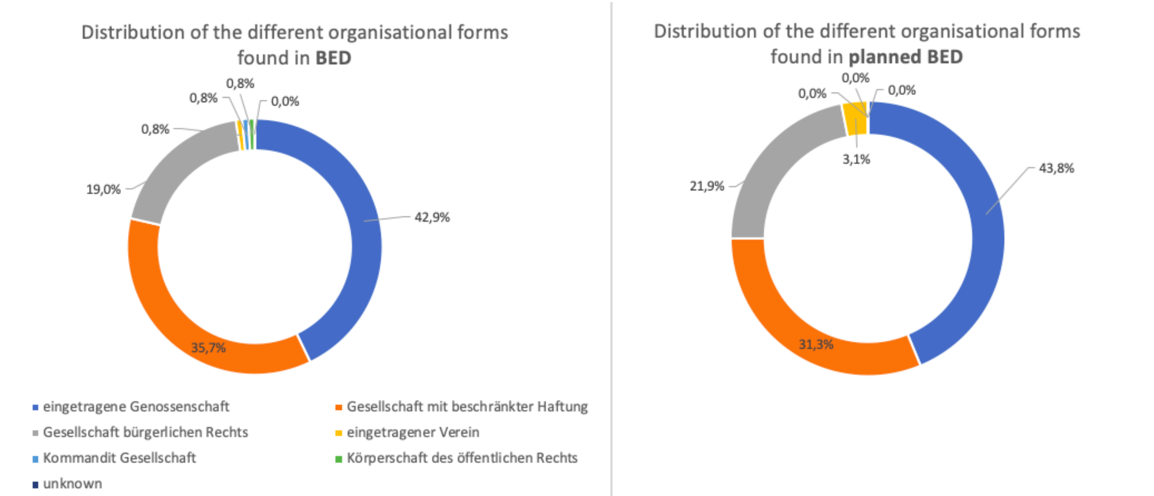

Figure 7.1: Occurrence of different organisational forms BED (left side) and pBED (right side)

The dispersion of the legal forms is almost the same in the old acknowledged BED projects as it is in the new not yet acknowledged and planned BED projects. The main legal forms that were found in the analysis were with approx. 43% the legal form of a registered cooperative (e.G.) /"*eingetragene Genossenschaft*"), followed by the legal form of a limited company (GmbH/orange color) and finally the legal form of a civil law association (GbR). All other legal forms that occurred, were according to my analysis not the main legal form, but rather a "sub legal forms" existing among others and being the basis for the main legal form that I noted.

7.2.2 Regional distribution of Bio-Energy-Villages over Germany's federal states

The post-code and name of federal state were extracted from each data-sheet in order to show the regional distribution of BED and pBED due to the diverging availability of RES of instance biomass, wind and solar radiation - the external technological RES as analyzed in Chapter 6, but also aiming at the subsequent qualitative socio-organisational barrier analysis.

Figure 7.2 below depicts the distribution of the BED over the different German states. Acknowledged BED accumulate to two-thirds on four states, which are primarily Baden-Württemberg (BW) with 29.6% of all BED, Bavaria (BY) with 27.6%, Niedersachsen (NI) with 11.8% and Hessen (He) with 9.9 %. This is slightly different with the non-acknowledged, 'newer' pBED, where more that 80% is accumulated on four partially different German states. The majority of pBED is projected in BW (38.9%), followed by NI (25%), BY (16.7%) and the north-eastern state of Mecklenburg-Vorpommern (MV) with 11.1%.

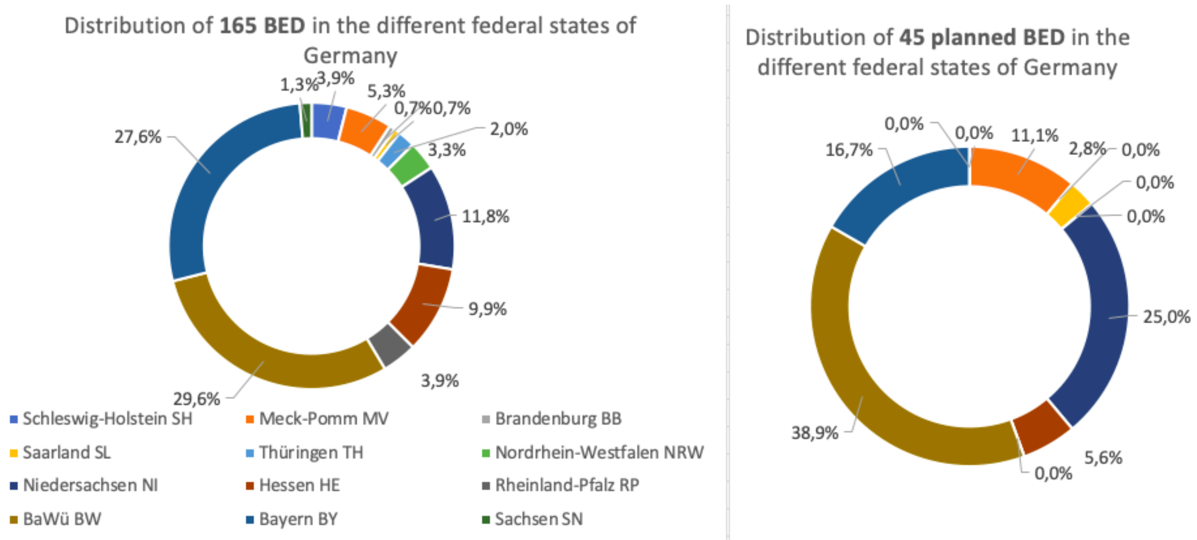

Figure 7.2: Distribution of BED (left) and pBED (right) in the 16 different federal states of Germany

7.3 Methodology description: guided interview on barriers

In order to tackle this sub-research question the methodology of a guided interview was developed that is presented in Figure 7.3. The following chapters explain how the barriers and questions where chosen that are depicted in Figure 7.3 on the bottom left under "Development of guiding questions". Further, chapter 7.3.1 depicts how the guided interviews were conducted, the information processed and the experts(' groups) on SDH and BED chosen - depicted in Figure 7.3 in the top.

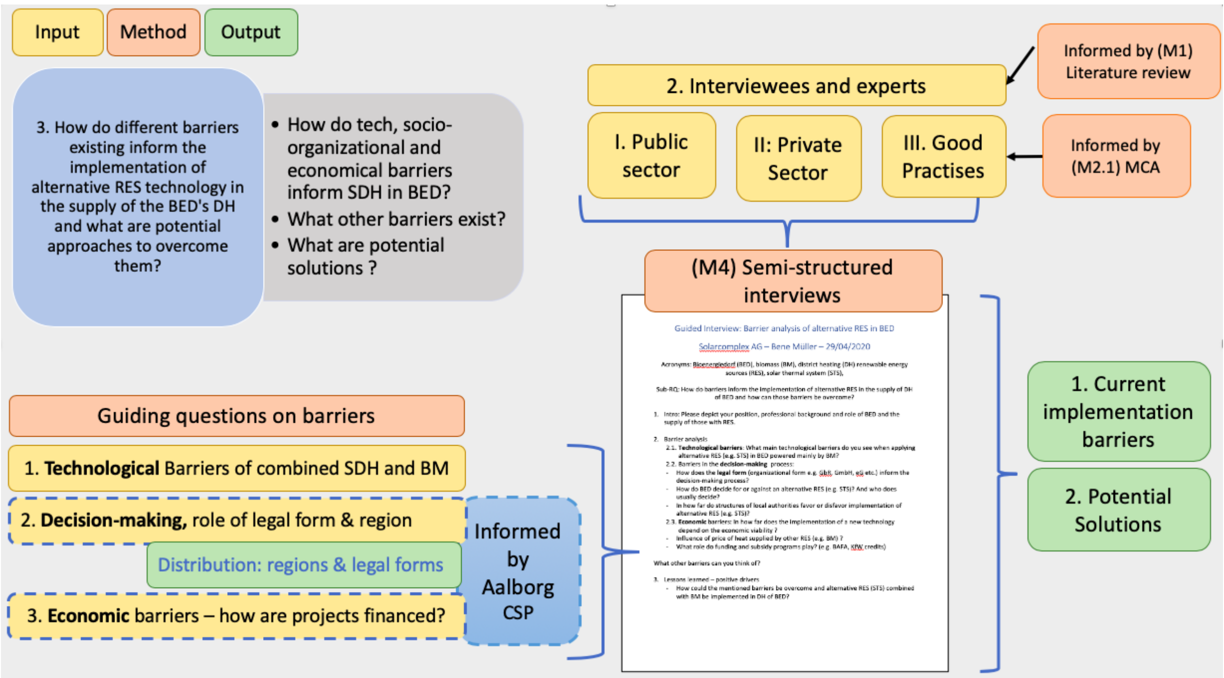

Figure 7.3: Research Design of the methodology of the semi-structured interview

7.3.1 Process of semi-structured interview and subsequent reviewing

All semi-structured interviews were conducted between April 23^{rd} and 30^{th} in form of (video-)calls lasting approx. between 30 and 75 minutes. In order to conduct the semi-structured interviews a questionnaire containing guiding questions was shared beforhand with the interviewees. In general, the guiding questions were the similar for some interviewees invalid questions were re-formulated or taken out. Generally, I started off explaining (i) the results of the techno-economic potential analysis of the BED (depicted in 5) and (ii) my background of the master-project as a student at Aalborg University. Further, I mentioned that I have been having a (iii) student job with the Danish company Aalborg CSP - a Danish company that is also projecting and planning STS and SDH projects and implements these accordingly. Aalborg CSP has a certain interest in understanding the potential for SDH in Germany. Though, I am not directly involved in planning SDH with Aalborg CSP during the thesis, so that my research and also the questions are partially influenced or biased by my student job. Moreover, I depicted that I am not recording the interview, but that the information given by the interview partners would be treated confidential if wished for. In the next step I started conducting the interview according to the developed structure with questions (see 7.3.2) that I had in advance shared with each interviewee. In the course of the interview, I tried to guide it by (slightly) pointing back to the questions, when the interview partners got lost in details. While they answered and explained, I took written notes of what I considered the most essential statements of each respective interview. After the interview I corrected my notes to subsequently share the documented resulting information with the experts for them to review, correct and amend the documentation or simply discard irrelevant or unwanted information noted by me.

7.3.2 Input for semi-structured interview - experts and questions

In order to understand the barriers that exist and further curb the development of SDH in Germany, on one hand, people with expert knowledge and working professionally in the field of SDH, BED and BM were chosen for the interviews. On the other hand, questions on different barriers developed serving as guideline for the interview. The following chapter explains the depicted questions on the barriers and how and why the group of interviewed experts were chosen.

Structure of Interview and types of barriers

The interviews were divided into three blocks. The first block contained a short introduction of the interviewer (me) and the interviewed expert, the second block was on the different barriers that exist in the implementation of SDH or other RES fuelled capacities for heating the BED. Lastly, a third block on potential solutions on barriers. The barriers and subsequent questions are listed in the table 7.1 below:

Intro and contextualization	- Please depict your position, professional background and relation to BED and the supply of those with RES.
(B1) Technological Barriers	- What main **technological barriers** do you see when applying alternative RES (e.G. STS) in BED powered mainly by BM?
(B2) Decision-making barriers	- How does the **legal form** (organizational form e.G. GbR, GmbH, eG etc.) influence the **decision-making process** of a BED towards alternative RES technology? And who decides in BED? - In how far do structures of local authorities favor or disfavor the implementation of alternative RES (such as solar thermal)?
(B3) Economic and financial barriers	- In how far does the implementation of a new technology depend on the economic viability? - What is the influence of the price of heat supplied by other RES (e.G. BM) ? - What role do funding and subsidy programs play? (e.G. BAFA, KfW credits)
(B4) Other barriers:	- What other potential barriers can you think of?
Potential Solutions:	- How could the mentioned barriers be overcome and alternative RES (e.G. STS) combined with BM be implemented in DH of BED?

Table 7.1: Guided Interview Outline - Solar District Heating and Bio-Energy-Village related experts

Asking for **technological barriers** goes along with deepening the analysis of technology potential. In case of current major technological hindrances in the application of SDH technology the result could extend the analysis on the technological potential (compare 5). Asking for barriers 2 and 3 was influenced by employees of Aalborg CSP hypothetically assuming that many projects are not implemented basically due to economic restrains. Further barriers in the decision-making process referring to the (group of) persons that decides for or against making the effort to install new renewable capacity. These questions aim at understanding why and how certain decisions for or against SDH were met while investigating the influences of these decisions. My hypothetical assumption here was that though the decision-making process does not go hand in hand with the legal form (which distribution is presented in section 7.2.1 above) - that it is likely to find a certain correlation in regard to how the different legal forms of the BED impact the decision-making process for or against certain alternative RES (such as SDH) itself. The final and forth question on the barriers aimed at leaving the interviewees the possibility to come up unknown potential barriers outside the guiding framework. In the third and last block the experts were asked if they are aware of any solution that have been used to overcome or could potentially be used and applied to overcome the (specific) barriers described in the second block.

Groups of interviewees

In total, three groups were selected that do work in the field of SDH and BM, a combination of those and in relation to BED. The first group consists of (1.) public institutions that the IBEG e.V.(registered association) and the FNR can be considered as. The second group includes (2.) private corporations. This group was chosen based on the assumption that it is the private sector which usually implements innovative projects such as SDH in BED in the German economic sector - among the requested relevant institutions were "*Hamburg Institut, Solites and Solarcomplex AG*". The third group results of the MCA (see chapter 5 preseting th only two BED that have combined installed SDH and BM capacities. Explanation: here a SDH refers to large-scale STC fields that feed into a DH system and not some arbitrarily, not strategically and decentralized small STS on private rooftops with low efficiencies. In total, seven interviews were conducted. Subsequently, the groups are enumerated comprising in paranthesis the number of interview - for instance: i-x represents interview number x:

1. Experts from public institution: FNR (i-1) and IBEG e.V.(i-7)
2. Experts from private institutions that work on BED and SDH: *Solarcomplex AG* (i-5) (i-6), *Hamburg Institut* (i-2)
3. Good Practises: Bio-Energy-Villages that have Solar District Heating **and** biomass heating capacities installed (i-3) (i-4)

The following table gives a short overview of the seven interviewed experts, the organisation or institution that they represent as well as a short description of their position, respectively how they fit into the research context and when the interview was conducted.

(No.) Interviewed	Organisation	Professional position	Date
(i-1) Dr. Hansen	FNR	responsible for BED and in Public relation department	23.04.2020
(i-2) Dr. Westholm	Hamburg Institut	Political and environmental sociologist working at SolnetBW	27.03.2020
(i-3) M. Rudewig	BED Mengsberg (Hessen)	electrical engineer, managing board of cooperative (e.G.) BED, planned SDH with BM	27.04.2020
(i-4) H. Gröbmayr	BED Moosach (Bavaria)	climate-protection manager, founded energy agency and Moosach energy cooperative	28.04.2020
(i-5) J. Dürr-Pucher	Solarcomplex AG	Works for the RES agency in the state of BW and Solarcomplex AG	28.05.2020
(i-6) B. Müller	Solarcomplex AG	Director at Solarcomplex AG, built BM+SDH combination three times	29.04.2020
(i-7) G. Brandt (revised too late)	IBEG e.V	planned 10 BED and Jühnde (first BED)	30.04.2020

Table 7.2: Experts and professionals in SDH and BED for semi-structured interviews in chronicle order. A description the position of the interview partners are in Appendix B.

The German notes of all interviews were counter-checked and revised by the each interview-partners and subsequently translated into English being the working language of this report. Interview partner (i-7) did not revise the notes duly so that I excluded them from the barrier analysis. The interviews and revised notes can be found in the appendices of this report (Appendix 2 - external document).

7.4 Analysis of the interviews in the context of the research question

This section aims at analyzing the (at least) three-fold barriers for SDH in Germany by synthesising the opinions and viewpoints of the interviewees. During the reviewing process of the interviewees' answers I color-coded the on different barriers and depict them below accordingly.

7.4.1 B1 - Technological barriers

The interviewees from the two BED with a SDH (i-3) (i-4) did not stress any bigger complications or real technological barriers. (i-1) (i-2) (i-3) (i-4) (i-5) The technology of SDH combined with BM was described as "mature and entrepreneurably convertible" (i-6). Generally, most of the interviewees stated that there are no technological problems in applying SDH to existing DH systems, but still certain considerations required to be taken into account (e.G. legal, space) and that further some technical difficulties exist - explained subsequently: The main difficulty described by interviewee B. Müller (i-6), who has been involved in the installation of in total 5 SDH with BED is the availability of land which is needs to be close to the settlements where price-speculations (high rent, lease, price..) occur (i-6). Further, it is important for the installation of a STS that a DH systems exists, which should also be in proximity to the land site - if these two conditions apply the systems were described as "low hanging fruits" for the first application of STS by Dr. Westholm.(i-2) Moreover, some said it is important that there is a minimum heat-demand required which mainly depends on temperature level, age and insulation of the houses.(i-2) (i-6) (i-5) Moreover, two interviewees said that DH in general, but also specifically combined with SDH, is only relevant to build in existing building stock and not in neighborhoods with newer low-energy insulation standards that do not require sufficient heat energy to run to reach (economic feasiblility (i-4) (i-6) (i-5). So far, there are no projects in Germany with solar fractions higher than 20%, thus yet no bigger TES have been installed (i-5).

M. Rudewig (i-3) from the **Good Practice** BED Mengsberg stressed that there were no major technological problems, still the technological considerations such as selecting the right size of components and adjusting the solar collector requires engineering skills and the energy system design issue that required engineering capacities: primarily fitting the thermal storage system with the bio-mass boiler (i-3). In the conduction of the BED Moosach, Bavaria (i-4) there were no technical barriers, but again the difficulty of finding enough small consumers was mentioned since the BED does not have bigger single heat demands (e.g. indoor pool). Also, the (i-1) interviewee from FNR stated not to know off B-1 related problems in any of the BED projects of Mosach and Büsingen, which both run a SDH and a BM. In general, Dr. Hansen (i-3) mentioned that there is a further general difficulty concerning users of private small-scaled STS home-systems, that are "competing" against other forms of RES generation. The situation emerged that STS do not have the best image among the users, as they would transfer the negative learning experiences from STS home-systems to larger-scaled STS respectively SDH. (i-1)

7.4.2 B2 Decision-making processes and legal form

Almost all interviewed experts explicitly stated the importance of a "wo*man of action" or "maker" - also possibly represented by a group of engaged people. (i-1) (i-2) Dr. Westholm mentioned that looking at past projects in the state of Baden-Württemberg (BW) he could specify for most projects the "maker" of each project. Usually, one needs such a person on the local level to promote a different and new technology (such as SDH). (i-2)

This can be confirmed by the interviewee from BED Mengsberg, who stated that in their project the forest-management ("*Waldvorstand*") and the district mayor ("*Ortsvorsteher*") were very engaged in the project's working group and its implementation. The "makers" also convinced other local people to participate in the energy cooperative of BED Mengsberg (more below). (i-3) There are **regional differences** in the BED's decision-making processes observable, since the community structure in the southern federal states is generally described as more pronounced and sound than in northern Germany. Specifically, in southern Germany (BY and BW) there exist more forest-associations and machinery syndicates ("*Maschinenring*") that are entangled with and supported by the local community. Whereas, in northern Germany - for instance in federal states of Schleswig-Holstein, Niedersachen, Mecklenburg-Vorpommern - there are some big agricultural farmers. Often local residents do not want to cooperate with those big farmers, if they for instance install a BG facility that could supply heating. Here it is more difficult to find majorities in the BED for a DH (or consequently probably also SDH) because of the insecurities of alternative RES after the 20 year term of EEG for BG. (i-1)

Mayor and municipal council

Generally, when executing SDH and BM heating projects three hurdles in the decision-making were described by B.Müller (i-6). The first is the support of the mayor, which was described to be the "Achilles tendon"(i-6) - without him*her, a project implementation is very unlikely to happen. Second, comes the city council, that needs to back the mayor's decision, but can according to B.Müller be convinced by excursions to SDH projects. The last hurdle is finding enough households (respectively HD) that are willing to connect to a DH - this is usually the biggest barrier according to interview (i-6). Interviewee (i-5) said that projects cannot be conducted without compliance of the mayor, the local farmer (land) and/or a couple of technology enthusiasts (i-5). Interviewee (i-2) described the importance of other institutions and authorities that have an eligible say in the affair of implementing a new technology. These vary from case to case and can range from an environmental and energy authority, over an agricultural authority to a nature protection authority (i-2). Consequently, the decision-making process does not only depend on the mayor and the city council. This can be confirmed by the the Good Practise from BED Mengsberg, where interviewee (i-3) asserted that local authorities were "very important to consider" (i-3) and further being entangled with social hurdles, since anyone knows anyone in the small community of the BED. In BED Mengsberg it was especially important that the main municipality Neustadt financially supported the project and guaranteed for the loan (see also 7.5). In the BED Moosach the STS project was supported by the second mayor who was backed by the city council (i-4).

Differences due to legal form

Further, the interviewees did not mention a direct correlation between the legal form and decision making processes against or for a specific technology. On the other hand, interviewee (i-1) even explicitly stated that he could not see a correlation in all the BEDs he worked with . On one hand, the legal form **GmbH** is usually applied on or by utility companies. (i-5). (i-2) stated that, though GmbHs are city/village-owned they continue being profit-driven, which makes it more difficult to to convince them of alternative non-conventional technologies. On the other hand, city-owned utility companies are more likely to raise the investment costs than citizen cooperations. (i-5) **Energy cooperatives** ('eingetragene Genossenschaften' - e.G.) were described as a good concept as such, since the e.G. only serve one purpose which is securing the supply of energy while further enabling the direct participation of citizens. Anyhow, a row of disadvantages were reported, so usually they require a certain initial (financial and entrepreneurial) support or 'kick-off'. Further, the knowledge about a certain technology is often accumulated in one person in the e.G.. Additionally, up to today in Germany e.G. have mainly been working on electricity generation and distribution (by wind and PV), and the model has not been largely adapted to heating concepts based on - for instance - SDH. This has the consequence, that as capital investments are larger and investment periods are longer the investment decisions are more complicated for e.G. to meet. (i-2) Further, it was said that the e.G. do not have an entrepreneurial approach, in consequence it is more difficult for them to conduct projects with a higher economical risk. (i-6) An alternative to the e.G. can be the municipality in form of an own-operating municipal enterprise. The advantage of this model is that the money stays within the community and and can be reused for new investments or for lowering the general heating price. (i-2) After implementing a e.G.-project one interviewee estimated that a further wider spread development of SDH is likely to happen due to e.G. (i-5).

The BED Mengsberg (Hessen, Germany) serves as a Good Practise for the interviewee (i-3). He considers an involvement of the local citizens as a necessary and required step in order to find a good decision. Therefore, the BED Mengsberg decided in 2014 to found an energy cooperative with the legal form of an e.G. that only manages the energy issues and does have the least level of interference with other local community institutions. The main arguments were it (e.G.) was the only legal form where everyone has the exact weight of vote. A second argument was that the legal form of an e.G. allows for certain tax savings (not further explained by interviewee). (i-3) In the second BED: Moosach, Bavaria, the initial plan was to also organize the DH as e.G.. For reasons of funding it then was implemented as a communal project as own-operated municipal enterprise ("*Eigenbetrieb*"). Because of this, the heating project could receive the Bavarian funds of the 'Village-Renovation Program' (i-4) ("*Dorferneuerungsprogram*") [Bayrisches Staatsministerium für Ernährung Landwirtschaft & Forst]

7.4.3 B3 - Economic barriers - funding programs

Subsidy programs are generally considered important and necessary for the implementation. Without them most of the SDH projects would not have been established. (i-1) Also, for nudging the further development of the SDH funding programs were be considered as highly important. Though, some BED projects (without SDH!) are known to be able to run feasibly without subsidy in federal states of southern Germany - such as BY and BW (i-2). One can generally observe a argument for instance put forward by B.Müller who further stated that less combined SDH and BM projects would have been conducted, if the full costs had to be carried by the project owners. (i-6) An interesting down-side of the subsidy programs was mentioned, which is the case of an over-subsidized project. In order to establish the SDH of Ludwigburg-Kornwestheim (in BW) several subsidy programs were accumulated and combined so that 60% of the project was highly leveraged. A critique to this was that such high subsidies are likely to be unsustainable for the development of other projects since such high subsidies are not possible or realistic for upcoming projects .(i-2)

A result from the interviews is that the cheap **price of oil** has an impact on the decision-makers and presents an economic barrier. One interviewee posed the example that he knows of municipalities that decided against a RES-fuelled heating system, because the oil-boiler was three times cheaper (i-1) in a short-term perspective. B.Müller from the "*Solarcomplex AG*" even estimated that only about 5 to 10% of the people are willing to actually pay a higher price for a less environmentally damaging source of heat. Though, in general it is rather the mid-term oil price that impacts decision makers and not the momentary prices - such as the negative oil price related to the oil capital-market crisis triggered by the COVID-19 Pandemic. (i-6) According to one interviewee there are various examples where citizens decide against BM or other RES technology, since they know that the natural or fossil gas is a thrust-worthy technology and cheap(er) to purchase (i-1). The **economic feasibility** of the implementation of a SDH depends, not only on the oil price, but also on the price of BM. As BM has such a comparably low energy density, it is only worth transporting it within a radius of <50km, but rather less. (Note: the match between the estimated guess and assumption of a "BM-radius" of 50 km in the technological framework analysis and the statement of the Bavarian interviewee is coincidental) (i-4) Furthermore, an economical interest from the side of the forestry-associations especially in southern Germany (BY and BW) was mentioned. These want to supply the local DH system with forestry and wood residues, which that is described as a plentiful resource in Southern Germany according to the first interviewee (i-1). Due to climate change, bark beetle attacks and increasing storms trees were chopped down, thus there is currently an oversupply of (mostly low quality) wood, that causes a low BM price. (i-1) According to (i-6) this has been having a positive effect on new projects supplied with BM. (i-5) stated that BM can act as a very good heat energy storage when turned off in summer. For SDH, the positive side-effect exist that the BM boiler does not need to run in part-load which causes additional costly abrasive wear.(i-5) Generally, a **critique** mentioned regarding the funding of solar facilities is the **EEG-funding program** (see also 4.7) that only aims at photovoltaics (in general at electricity generation) within solar technologies. In contrary, STS (heat generation) is not included. As to this displaced funding focus STS in general, but also especially in solar energy face a lack of funding. (i-1) Other economical barriers in STS projects are the leasing or rental prices of the site, which are as to the BED Moosach interview especially close to high population density and economic density areas such as Munich - scarce and expensive (i-4). One interviewee said that due to the stop of EEG for BG CHP boilers 20 years after installation only second generation biomass (from residues) is able to survive on the market and not BG from corn especially grown for use as BG (i-5).

7.4.4 B4 - Other barriers

Other barriers mentioned are the utilization rivalry between RES and other industries, the dependence of the consumers on the operator of the DH system (in the case that it is externally-operated), and that a STS has aesthetic constraints for the landscape. Further, there are usually legal barriers with for instance building laws and that decision-makers are sometimes simply unmotivated, which makes it hard to implement projects. (i-2)

Social Barriers

One interviewee (i-6), who has been involved in many projects combining SDH and BM described the social hurdle of convincing and explaining the advantages and the actual lower price compared to fossil fuels. When applying a full cost calculation - to the people as the biggest barrier. Moreover, large-scale SDH as a technology is widely unknown in Germany (i-1) (i-2). This has the consequence that hardly excursion or visiting sites exist, where planners or city councils are able to visit Good Practice examples (i-1). Energy planners in northern Germany asked experts from southern Germany for consultancy without noting that there are experts in Denmark.(i-5) Some projects were not only pushed forward because of economical reasons, but also for political and environmental reasons. In the BED Mengsberg there was no obligation of a certain minimum heat take off, which lead to a demand problem as some people decided to have both heating systems: the traditional oil boiler in a cellar room and the connection to the DH system with the intention to (miss-)use the system by consuming from the cheapest heating sources. This had the consequence of a decreased total heat demand of the DH system, which let the (household) specific heat price rise.(i-3) In BED Moosach the people feared that being connected to the DH would make them dependent on the DH operator *NaturStrom AG* and they wanted to maintain their autonomy and self-sufficiency (i-4) - though they might be immediately at least as dependent on fossil oil and electricity enterprises along the supply and production chain. According to (i-4). Some people living close to the BM boiler feared that they would be additionally contaminated by emissions.

Political

Though, there are some supportive research programs that also apt for large STS and/or SDH, also broader programs (such as *Wärmenetze 4.0*) - but these programs are generally not known enough. (i-1) Some states (e.g. HE) and also communities have agreed to the Sustainable Development Goals. As to Dr.Hansen for them to reach these goals is hardly possible without addressing heating and alternative technologies such as SDH. (i-1)

Legal Barriers

According to Germany's building law ("*Baurecht*") a legally binding land-use plan ("*vorhabens-bezogener Bebauungplan*") is required to actually start to install a project. One interviewee explained that it usually lasts one year to get such a building law permission. (i-6)

Strategic planning

Dr. Westhof from *Hamburg Institut* explained the existence of strategical barriers or that he observed that strategies behind planning processes were often missing. He put forward the example of the natural gas pipeline system that needs to be replaced in the mid-term in many place if the country wants to reach its climate goals. (i-2) That means, that when work is conducted on DH-pipeline system, the planner should bear in mind other strategic infrastructures. For instance installing glass-fibre internet connection or the above mentioned removal or replacement of natural gas pipelines.

7.5 How could the specific barriers be overcome?

This section briefly explains potential approaches on how to overcome specific barriers.

7.5.1 Technological Barrier

Due to the fact that no real technological barriers exist, respectively they have not been identified with the applied method of expert interviews. However, it requires planning and engineering skills to synchronize the supply side with the demand side well. (i-6)

7.5.2 Social Barrier

Large STC fields and SDH is unknown in Germany. In Moosach in was overcome by residents participating in an excursion to SDH plants by the company *Arcon Sunmark* to Denmark - since example projects in Germany were/are lacking. (i-4) Overcoming social barriers was described possible by having "good, sharp and better" arguments. Interviewee (i-3) proclaimed that arguments on the need of the energy transition in general, climate protection, price-insecurity due to oil-price fluctuations and (energetic) independence could convince the people to join the energy cooperative and thus support the role-out of SDH. Another argument against BM and for a STS is what interviewee (i-3) called 'wood-labor', so the labor required to run a DH system on BM (such as chopping, stacking etc.) which would be decreased running the DH also on a large-scale STS. (i-3) gave an example on how the German energy giant E-ON offered a at first glance "cheaper" fossil gas fuelled heating system to the BED Mengsberg. Whatsoever, the offer was rejected by the BED community due to climate-protection reasons and the goal to establish a 100% RES system.(i-3) This example serves as a Good Practice on how a community makes an autonomous decision by rejecting a centralized fossil fuel energy system while ensuring a community-centered renewable energy future. Another solution put forward finds itself at the intersection between the social and the economical barriers and refers to the capital price of the system and is explained in the next subsection below.

7.5.3 Economic Barrier

A full-cost calculation ("*Vollkostenrechnung*") was considered a good tool to show residents that heating from RES is eventually cheaper than the oil price, in which often maintenance, extra room, a tank-system, a chimney sweeper and other technical appliances are excluded. (i-2) (i-6) This should usually be happening in or via a public event, so that a full-cost calculation of the heat price can be conducted and further avoiding individual calculations and consultations. (i-6) In the BED Mengsberg the investment could be covered due to two reasons. First, the *KfW-Kredit* (loan) that allowed to fund partially the thermal energy storage system, the biomass-boiler and the STS. Secondly, the main municipality guaranteed for the project, so the credit's interest rate was kept low. Subsequently, the heat price was at 10.5 € cents/ kWh_{th}, which is cheaper compared to the heat from an oil-boiler with a full cost calculation. (i-3) In Moosach, a full cost calculation was also made to convince local residents to join the project and a combination of the Bavarian "Village-renovation Program" and the *KfW-Kredit* was required to launch the project (i-4).

7.5.4 Political

The Interviewee (i-2) mentioned that, according to his experiences with the *SolnetBW* project, legal binding guidelines for municipalities keep certain land areas free and assign them to a purpose such as STS.

Carbon-tax

In 2021, a carbon-tax will be introduced in Germany that is likely to have a positive effect on BED in general but also SDH. (i-1) On the other hand, interviewee (i-2) warned that it is likely for the tax not to have an influence if it is set too low. Also, interviewee (i-3) mentioned that a carbon-tax should help and push the implementation of SDH, but that the tax is required to rise to really have an impact on the price.

phasing out EEG-subsidies for BG

Since the financial re-compensations of the EEG for BG is being stopped after 20 years - with some exceptions due to flexibilisation ("*Flexibilisierung*"), where the financial re-compensations can be prolonged for another 10 years. It is as to Dr. Hansen relevant to know when the facilities are actually being shut down and stop electricity and heat production. (i-1)

Germany's exit from coal

Germany is phasing out coal by 2038. This means that also power plants which supply district heating today will not be running anymore. According to the second (i-1), one as energy planner should bare this opportunity in mind, since the old power plants are often located outside the cities (due to emissions) and often surrounded by multiple hectares of wasteland that could be a potential for harvesting thermal radiation from the sun. (i-1)

7.6 Summary, conclusion, limitations and outlook

The following boxes summarize the analysis of this chapter and further seek to draw conclusions from the existing barrier analysis by showing potential approaches on how these can be overcome. The main conclusion is that it seems that though socio-economical, organisational and decision-making barriers can be observed, the heating transition in Germany is best positioned to be tackled by community-owned projects of alternative RES. Despite this, Germany and its federal states requires further legal, strategic and political measurements and instruments to increase the roll-out of SDH to reach the solar thermal goals described in section 4.5.3. In general, Germany and its native BED already seem poised to undergo the heating transition from a financial and organisational level.

Summary from result section 7.4

- No larger technological barriers were found. STS and **SDH technology** are **mature for application**. Generally, only smaller technical difficulties exist by planning engineers. The main technical difficulties lay rather in the framework conditions, for instance finding the right (proximity) site and enough households (heat demand) for the DH network.(see 7.4.1)
- DH in general and SDH can only feasibly operated in older building-stock, since newer low-energy houses have too low of a heat demand.(see 7.4.1)
- There are negative learning experiences and potential bad images from small-scaled home-systems in which BM was combined with STS. (see 7.4.1)
- Most interviewees clearly stated that the decision-making process usually requires a group of **maker(s)** .(see) Further, usually it is important that the mayor supports a STS project, who needs to be locally backed - in the best case by the city/municipal council. (see 7.4.2
- According to the interviews, though the **different legal forms** show to have advantages and disadvantages for the community, **no direct correlation** with the **decision-making** process for or against an alternative RES technology is observable. (see 7.4.2)
- The two main legal forms occurring are e.G. and *GmbH* - which seems to present case-specific (dis-)advantages. (see 7.4.2) The interviewees did not mention *GbR*
- The community structure of rural BED seem to differ between closely linked (in a social sense) and smaller farms in the south compared to bigger and rather impersonal farms in the north. (see 7.4.3)
- The current **funding programs** are necessary for the further development of SDH in BED. Without the funding programs, there would clearly be an economic barrier and less (combined) SDH and/or BM projects - though the funding should not be too high. (see 7.4.3). One policy option would be to implement a lower and upper subsidy limit in the form of a "funding corridor".
- Other - namely, political legal and strategic - barriers exist. (see 7.4.4)
- The main barrier seems to be social, manifesting itself as (i) SDH being an unknown technology in Germany, (ii) a supposedly higher price of SDH compared to other technologies. (see 7.4.4)

Summary of solutions to barriers and concluding remarks from section 7.5

- A solution to the social barrier is **excursions** to successfully operational combined SDH and BM projects. I consider it paramount to have at least one "Good Practice" **within** Germany as excursion object to demonstrate the potential for these projects domestically.
- Arguments on climate change, environmental protection and less CO_2 emissions did contribute positively to decision-making, and should be used when arguing for replacing fossil fuels. I suggest to have a stance in this argument, by knowing results of for instance **environmental and social impact assessments of SDH** technology.
- The community's wish to be self-determined, and autonomous in their decisions on energy issues, hence the **reliability of SDH systems** should be put forward as an argument.
- Price-efficiency of SDH - **Full-cost calculations** turned out to be a good tool for overcoming the socio-economic barrier of the supposedly lower heat-price of oil and also CHP fueled by biogas and biomass, once the EEG-funding stops.
- Further nudges that could favor SDH in the future are political instruments such as encouraging Germany's phase-out from coal through use of **2021's CO_2-tax** (truly taxing).
- The complete **phase-out of electricity EEG-subsidies** on BM and BG generation and introduction of **EEG-funding on heat generation** would potentially favor SDH.
- Official **heat transition strategy** including policies, such as assigning STS fields for each municipality, are (often) lacking and should be developed on a (local) government level.

A potential **limitation** of this method is that categories (B1, B2, B3) were pre-determined and guided as described and thus supposedly impose a bias of sorts on interviewees as they could not freely talk. I tried to circumvent this by framing the final interview question as an open question to address any barriers. Further, the interviewees' answers were not compared to literature on RES application (potentially scarce) in villages/BED. Another critique on the method is that mostly professionals favoring the technology and approach of SDH were interviewed. There was no representation of those opposed to solar thermal energy technology. This would have been very useful, especially in the phase of understanding social hindrances.

Potential **research findings** I consider favorable and necessary for further understanding the barriers are: first, analyzing how well-suited BED with a high potential from chapter 5 evaluate the option to expand the BED's heat supply. Interviewing experts that are likely to (negatively) criticize SDH in order to see the negative consequence of the use of this technology and form a holistic perspective on SDH would also address the barriers outlined above. Secondly, assessing specifically the social impacts of solar thermal technology on a Bioenergy-Village level in order to include the input of the local people. This would allow for the just implementation of new RES technologies enabling a eco-socially sound transition towards renewable energies villages.

8 | Discussion, limitations and outlook

Humanity must transition its energy systems in order to avoid the catastrophic consequences that the extraction and burning of conventional fossil fuels are causing. In Germany, the transition towards a renewable fuel energy system is underway exemplified by the rural Bioenergy-Village movement. Today, Germany's heating sector is only 14.5% supplied by renewable energy sources (RES), of which two thirds are covered by biomass and only 5% by solar thermal. Solar Thermal Systems (STS) were found to be about 50 times as land-efficient as biomass. On one hand, the country's demand for BM is growing, even though it is a limited domestic energy resource at the root of some conflicts, such as land-use disputes. On the other hand, the number of STS is stagnating in Germany. In 2019, only 62,700 m^2 out of 19.3 M m^2 were comprised of 34 large-scale STS. Further, many scholars find that district heating (DH) and individual mixes of RES are required for a fossil free heating sector.
The research subject "*Bioenergiedörfer*" (BED) cover their heating demand with DH supplied by at least 50% RES, with the majority of these being biomass and biogas. These energy systems also tend to make use of alternative organisational forms (see 4.1). The increasing occurrence of BM scarcities has led to the proposal of transforming the BED to renewable-energy-villages as a potential solution. [Jenssen et al., 2014] To that effect, there are 159 BED and 45 planned BED (pBED) currently in Germany promising to advance the domestic heating transition through citizen energy projects. However, their overall techno-economic potential for SDH has not been estimated yet. For determining the optimal share of the different individual RES technologies, it was considered important to look into the surrounding external technological renewable resources available for each BED. Accordingly, the biomass residue potential for limited biomass was analyzed as well as the potential socio-organisational barriers hindering a build-up of SDH in the BED. This flowed into the main research question presented in Chapter 2.

Discussion of results

A multi-criteria analysis (M2.1) was developed and utilized for finding the techno-economic potential on the supply side. Two groups of BED could be found that suit an implementation of SDH. First, 15 BED exist that have BM units of more than 1.5 MW_{th} installed and could suit SDH, since the fuel and wood-chips can serve as seasonal fuel storage and be burned when required. Second, as the EEG-funding on CHP is being phased out, 9 BED have BG-based CHP units that are likely to (partially) stop their energy generation and thus can be poten-

tially replaced by other RES technologies such as SDH. After I had obtained FNR-data into the data-sheet, I became aware of a "meta-analysis" based on the BED data-sheets of BED from 2015 containing 160 BED [Folker and Eigner-Thiel, 2016]. On first sight, the overviews seem to point into a similar direction - though the data was not used for more than an overview. Whereas, I further the spread-sheet for assessing the BED's techno-economical potential, which main finding were the following: the annual heat demand of all BED and pBED is around 2100 GWh_{th}. In total, 104 BED and 35 planned BED show to have supply rate of less than 70%, and a heat demand for a solar fraction of 20% (C1 in Table 5.1) which equivalents a total STC field of about 270,000 m^2 is the estimated technological potential for Germany's BED and pBED. Second, if a minimum heat demand (C2) equivalent to a field size of 1000 m^2 is additionally assumed, the theoretical STC area potential is about **238,000 m^2** in 56 BED and 18 pBED. This is equivalent to about four times the 62,700 m^2 of large-scale STS currently installed in the country (compare 4.5.2). Additionally, equipping all **74 potential BED and pBED** with SDH with a solar fraction of 20% would incur a **base capital price** of around **121 M €**.
The second analysis shows the indicative theoretical energy potentials (REP) of three types of BM surrounding each BED in a radius of 50 km. The average REP values in the immediate surrounding of each BED and pBED for forest, agriculture and livestock are 8.60 PJ(ranging from 1.3 to 13.73 PJ/a), 2.47 PJ (ranging from 0.34 to 5.71 PJ/a) and 2.09 PJ (ranging from 0.5 to 6.33 PJ/a) respectively. For each type of REP, a bottom group of BED can be identified that has the lowest access of each type of REP. These are likely to be confronted with a limitation of the remaining unused biomass potential (see also 4.2.3). - especially those with low forest REP and BM-boilers that require solid BM. At this stage, I consider it recommendable to make use of biomass REP values as indicators and to integrate them into a more profound MCA analysis. The Hotmaps project [Hotmaps Project] that intends to bring the demand and supply sides together, but do not allow for an assessment of the coordinate/village - specific BM, what should be taken into consideration.
Generally, the findings from the (M4) semi-structured interviews seem to overlap in the results of survey conducted by (see section 7.1 and [Geiger, 2019]. The following **recommendation for implementation** can be provided on basis of the interviews: First, different legal forms used in Germany's BED do not seem to strongly influence the decision-making process for a new RES technology in the DH network - whereas the location of BED within Germany (northern or southern state) do show to have an influence. Second, a (group of) "maker"(s) and the backup of the mayor and city council is needed to implement any RES project. Conducting any RES project, the "makers" need to be known and the backing of the mayor must be secured. Third, the current funding programs are considered a necessary condition for a further roll-out of SDH projects - though accumulation of funding should be avoided. It is recommendable to explain the heat price via a "full-cost-calculation" to economically compete against fossil fuels. Fourth, the social barrier on the fact that large-scaled thermal collector fields as part of SDH are widely unknown in Germany and only few SDH exist - for that reason it can be recommended to find a Best Practise within Germany for excursions when conducting projects.
Further, policy recommendations found via the interviews could be: First, a (i) "heat transition strategy" on the federal states level that assign a specific space for SDH for each municipality, second, a (ii) (high) carbon-tax as policy so that these costs are noticed in a full-cost-calculation and, third, a (iii) "funding corridor" comprising an upper and lower funding limit.

Limitations

Method (M2.1)'s limitation is potentially calculated heat demand only depicts an approximation of district heating and not being representative of the whole village's demand. Further, the FNR's data-sheets did not allow an in-depth analysis, necessitating a meta-analysis to find suited BED. Moreover, there were some data gaps in the FNR's data-sheets, on both the supply and demand sides, so that some supply and demand sides could not be included in the analysis or had to be interpolated. The limitation of analyzing the (M3) GIS biomass REP that the calculation method sums up the "theoretical maximum REP" in a radius of 50 km (variable) around each BED. It does not account for overlapping with other BED's radii and potentially double-counts the REP multiple times. Further, the data-bases of the different REP are diverse and have a "district-sharp" (NUTS3-level) resolution, which likely does not allow to scale down the radius too much, however radii below 50 km are feasible expected be due to the size of the district in NUTS3-resolution. The limitation of (M4) socio-organisational barrier analysis via semi-structured interviews (chapter 7.3 is that it only focused on experts already favoring of SDH, BM and BED limiting the findings of the interviews to certain implementation barriers.

Further research: The COVID-19 pandemic's outbreak in March 2020 influenced this research design (see also Preface & Disclaimer), resulting in the research taking the form of a barrier analysis - interviewing SDH and BED experts and not BED-planners in situ. At this stage of my research, I consider a survey with energy-planners of for instance all 74 high potential as useful, to foster the understanding of socio-organisational hurdles of BED and to boost BED participants' awareness of SDH technology. However, groups of groups of high potential BED for SDH are known now, such a DH-model can be set up and and specifically adapted to some BED. When travels are permitted again (June, 15^{th}, 2020) high-potential (based on C1, C2) BED should be visited, to discuss the model, understand village-specific potentials, and gain insight into the specific situation and decision-making structures.
Regarding the BM spacial REP analysis, first, the assessment must take the REP of surrounding BED (and other villages) within the radius of a specific BED into account and be developed further towards merging each BED's REP with the REP of adjacent (BED-)villages. Second, this revised accounting method can be used to complete a supply side MCA that extends beyond the REP of BM to external RES as criteria. It could result in a village-specific matrix of all RES potentials (e.g. wind, solar, geothermal) and the BM REP. It should enable the energy planning process not only for BED, but for European renewable energy villages.
In a last step, the method of the Multi-Criteria-Analysis should be further extended to also comprise criteria beyond the RES and the technological supply and demand side. I would argue for it to also contain results from environmental (EIA) and social impact assessment (SIA) of solar thermal technology - as done in Denmark in other RES projects [Larsen et al., 2018]. The EIA can be based on, for instance, a full Life-Cycle Assessment of the technology or further comprise the "Energy return on investment". This potentially enhances a more ecologically and socially sound transition towards renewable energy villages.

9 | Concluding remarks

"*Bioenergiedörfer*" (BED) show to have to have a good potential to help with Germany's heat energy transition. 74 BED villages were found to fit the criteria for being suitable for supporting SDH, which are: (C1) a low supply rate of less than 70% m^2) and (C2) a heat demand equivalent to a SDH of 1000 m^2. They comprise a theoretical potential of in total 240,000 m^2 collector areas requiring a base capital price of about 121 M €. Further, other BED groups based on supply side criteria (high BM-boiler capacity, old BG-CHP capacity) could be determined that are well-suited for the implementation of other RES technology such as SDH from a technological supply side perspective. From a technological standpoint, based on the multiple-criteria-analysis four groups of BED meet at least one demand and supply side criteria and are thus suitable for SDH. It is recommendable choosing some individual projects and perform more in-depth analyses based on an energy-system model. Also, from an external RES perspective, the biomass residue energy potentials of each BED were assessed allowing to identify groups of BED with low biomass residues, that could be assigned with particular potentials for SDH implementation. This method is recommended to be included into the MCA method developed, but also other energy planning tools such as the "Hotmaps project". Moreover, the BED's socio-organisational landscape seem to provide a solid basis to further transition Germany's heating sector by implementation of SDH, though barriers exist. Decision-making processes seems to depend on the location of the BED within Germany, but unaffected by legal form chosen. Social barriers for SDH implementation are that the technology is mostly unknown, and that a maker is required to implement the project. The means to overcome these barriers are for instance, (1) excursion to SDH projects within Germany and providing (1) full-cost-calculations, but also policy proposals such as a (3) "funding corridor" prescribing a minimum and maximum to the subsidies or (4) binding municipalities to assign areas for solar thermal. Today, Germany's funding-programs support the development of SDH, giving a positive prognosis for the near future. However, in Germany's climate&energy politics absurdities are almost a daily occurrence. A prime example of such occurred on May, 30^{th} 2020, when the country powered up *Datteln4*, a brand-new 1.1 GW_{el} coal power plant WDR [2020] - ignoring the country's coal-phase out in 2038 and the fact that we are, globally, in the middle of the climate crisis. If Germany's federal government continues to perturb her "*Energiewende*" in this way and keeps political frameworks in accordance with the *Datteln4*-example, the one-time chance of transitioning on of the biggest economies, before climate tipping points are reached, is at stake - and so are fossil free and autonomous renewable energy villages using potentially convivial technologies such as SDH.

References

Agentur für Erneuerbare Energien. Die Brandenburgische Stadt Senftenberg ist Energie-Kommune des Monats Oktober 2016 - Agentur für Erneuerbare Energien. (Date Accessed: 2020-02-24), 2016a. URL https://unendlich-viel-energie.de/themen/waerme/solarwaerme/enegie-kommune-senftenberg.

Agentur für Erneuerbare Energien. Kombination aus Bioenergie und Solarwärme macht Neuerkirch und Külz unabhängiger von Ölimporten - Agentur für Erneuerbare Energien. (Date Accessed: 2020-04-13), 2016b. URL https://unendlich-viel-energie.de/presse/nachrichtenarchiv/2017/energie-kommunen-neuerkirch-und-kuelz2.

O. Akizu, G. Bueno, I. Barcena, E. Kurt, N. Topaloğlu, and J. M. Lopez-Guede. Contributions of bottom-up energy transitions in Germany: A case study analysis. *Energies*, 11(4):1–21, 2018. ISSN 19961073. do: 10.3390/en11040849.

Alexander Knebel and P. Vohrer. SOLARENERGIE UND BIOMASSE : WENN DIE SONNE DOPPELT WÄRMT. (Accessed: 01-04-2020), 2016. URL https://unendlich-viel-energie.de/media/file/561.AEE_RK_Bio_Solar_Dez16.pdf.

Arcon Sunmark. Dronninglund Projekt. (Date Accessed: 2020-04-13), a. URL http://de.arcon-sunmark.com/referenzen/dronninglund-district-heating.

Arcon Sunmark. Fjernwarme Silkeborg, Danmark. (Accessed: 2020-04-14), b. URL http://de.arcon-sunmark.com/referenzen/fjernvarme-silkeborg-danmark.

BAFA. BAFA - Bundesförderung für effiziente Wärmenetze (Wärmenetzsysteme 4.0). (2020-05-02), 2020. URL https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/waermenetze_node.html.

Bayrisches Staatsministerium für Ernährung Landwirtschaft & Forst. Dorferneuerung. (Accessed: 2020-05-04). URL http://www.stmelf.bayern.de/agrarpolitik/foerderung/004011/.

M. Berberich and T. Pauschinger. Energiedörfer - Umsetzung von neuen Solaren Wärmenetzen Kombiniert mit Biomasse. Technical Report Förderkennzeichen 691624, 2018.

BMWi. Energieeffizienz- strategie Gebäude. Technical report.

BMWI. BMWi - Energiedaten: Gesamtausgabe. (Accessed: 2020-03-31). URL `https://www.bmwi.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html`.

A. Brosowski, P. Adler, G. Erdmann, W. Stinner, D. Thrän, U. Mantau, C. Blanke, B. Mahro, T. Hering, and G. Reinholdt. Schriftenreihe Nachwachsende Rohstoffe Band 36 Biomassepotenziale von Rest- und Abfallstoffen (Status quo in Deutschland). Technical report, 2015.

E. Carpaneto, P. Lazzeroni, and M. Repetto. Optimal integration of solar energy in a district heating network. *Renewable Energy*, 75:714–721, 2015. ISSN 18790682. do: 10.1016/j.renene.2014.10.055.

Co2mmunity. Project website, Case Story Marstal Fjernvarme – a solar district heating plant on the island of Ærø , Denmark. *INTERREG project Co2mmunity*, (Accessed: 2020-04-19):1–4, 2019. URL `http://co2mmunity.eu/wp-content/uploads/2019/03/Factsheet-Aerö-Marstal.pdf`.

COP21. Home - Paris Pledge for Action. (Accessed: 2020-05-31). URL `http://parispledgeforaction.org/`.

J. Daniel-Gromke, N. Rensberg, V. Denysenko, T. Barchmann, K. Oehmichen, M. Beil, W. Beyrich, B. Dr.-Ing. Krautkremer, M. Trommler, T. Reinholz, J. Vollprecht, and C. Dr. Rühr. Optionen für Biogas-Bestandsanalgen bis 2030 aus ökonomischer und energiewirtschaftlicher Sicht. Technical report, 2020. URL `https://www.umweltbundesamt.de/publikationen/optionen-fuer-biogas-bestandsanlagen-bis-2030-aus`.

Deutscher Wetterdienst. Wetter und Klima - Deutscher Wetterdienst - Katastrophenschutz. *Deutscher Wetterdienst*, (Accessed: 2020-05-13), 2020. URL `https://www.dwd.de/DE/forschung/klima_umwelt/klimaueberwachung/klimaueberwachung_node.htmlhttps://www.dwd.de/DE/fachnutzer/katastrophenschutz/katastrophenschutz/katastrophenschutz_node.html`.

Drake Landing Solar Community. Borehole Thermal Energy Storage: DLSC. (Accessed: 2020-01-23), a. URL `https://www.dlsc.ca/borehole.htm`.

Drake Landing Solar Community. Drake Landing Solar Community. (Accessed: 2020-01-23), b. URL `https://www.dlsc.ca/`.

Dronninglund Fjernvarme, PlanEnergi, and Niras. Dronninglund Solar thermal plant. Technical report, 2014. URL `http://www.planenergi.dk/wp-content/uploads/2015/04/Brochure_Dronninglund_2015_booklet_ENG_web_.pdf`.

DTU Wind Energy and World Bank Group. Global Wind Atlas. *Global Wind Atlas*, (Accessed: 2020-05-13), 2018. ISSN 0035-8711. do: 10.1093/mnras/sts501. URL `https://globalwindatlas.info/`.

E-wie-einfach. Was ist das Erneuerbare-Energien-Gesetz (EEG)? | E WIE EINFACH. (Accessed: 2020-04-27). URL `https://www.e-wie-einfach.de/faq/faqs/was-ist-das-erneuerbare-energien-gesetz-eeg`.

Ecomodernism. EIN ÖKOMODERNES MANIFEST — An ECOMODERNIST MANIFESTO. (Accessed: 2020-03-18). URL https://www.ecomodernism.org/deutsch.

ESMAP, SOLARGIS, WB, and IFC. Global Solar Atlas. *Global Solar Atlas*, (Accessed: 2020-05-13), 2019. URL https://globalsolaratlas.info/?m=sg:ghi.

European Comission. Eine EU-Strategie für die Wärme-und Kälteerzeugung. (Accessed: 2020-05-26), 2016. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1575551754568&uri=CELEX:52016DC0051.

Eurostat. LUCAS - Land use and land cover survey - Statistics Explained. (Accessed: 2020-05-13). URL https://ec.europa.eu/eurostat/statistics-explained/index.php/LUCAS_-_Land_use_and_land_cover_survey#How_is_LUCAS_conducted.3F.

EUROSTAT. National structures (EU) - Eurostat. (Accessed: 2020-05-13), 2018. URL https://ec.europa.eu/eurostat/web/nuts/national-structures-eu.

Eurostat. European Countries - Eurostat. (Accessed: 2020-05-05), 2019. URL https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries.

Fachagentur für nachwachsende Rohstoffe. FNR - Bioenergiedörfer: Betreibergesellschaft. (Accessed: 2020-04-08), a. URL https://bioenergiedorf.fnr.de/wege-zum-bioenergiedorf/vorbereitung-der-bauphase/betreibergesellschaft/.

Fachagentur für nachwachsende Rohstoffe. FNR - Bioenergiedörfer: Was ist ein Bioenergiedorf? (Accessed: 2020-04-08), b. URL https://bioenergiedorf.fnr.de/bioenergiedoerfer/was-ist-ein-bioenergiedorf/.

Fachagentur für nachwachsende Rohstoffe. FNR - Bioenergiedörfer: Gründe für ein Bioenergiedorf. (Accessed: 2020-04-08), c. URL https://bioenergiedorf.fnr.de/wege-zum-bioenergiedorf/gruende-fuer-ein-bioenergiedorf/.

Fachagentur für nachwachsende Rohstoffe. FNR: Mediathek - Bioenergiepotenziale in Deutschland im Jahr 2050 - Videos. (Accessed: 2020-02-10), 2016. URL https://mediathek.fnr.de/videos/bioenergiepotenziale-in-deutschland-im-jahr-2050.html.

Facharbeitskreis Effiziente Stadt and Ritter XL Solar. Solare Fernwärme im Großformat - Beispiele in Kommunen Themenübersicht Aktueller Stand in Deutschland Varianten solarer Fernwärme Stadtwerke Senftenberg als Trendsetter Potentiale der Solarthermie. ((Via Contact at Lund university)), 2017.

G. Faninger. Combined solar-biomass district heating in Austria. *Solar Energy*, 69(6):425–435, 2000. ISSN 0038092X. do: 10.1016/S0038-092X(00)00117-1.

FNR. FNR - Bioenergie: Erneuerbare-Energien-Gesetz (EEG). (Accessed: 2020-04-27), a. URL https://bioenergie.fnr.de/klimaschutz/gesetze-verordnungen-richtlinien/gesetzeslage/erneuerbare-energien-gesetz-eeg/.

FNR. FNR - Bioenergiedörfer: Liste. (Accessed: 2020-02-20), b. URL https://bioenergiedorf.fnr.de/bioenergiedoerfer/liste/.

FNR. Bioenergiepotenziale in Deutschland im Jahr 2050 - YouTube. (Accessed: 2020-04-12), 2016. URL https://www.youtube.com/watch?v=LtSVyZORKxo.

R. Folker and S. Eigner-Thiel. 10 Jahre Bioenergiedörfer – Fortschritt neu denken. Technical report, 2016.

G. Garegnani, P. Zambelli, and Eurac research institute. README.md · master · Hotmaps / potential / potential_forest · GitLab. (Accessed: 2020-05-12). URL https://gitlab.com/hotmaps/potential/potential_forest/-/blob/master/README.md.

P. S. F. S. Geiger. Befragung von Marktakteuren zu zukunftsweisenden Konzepten zur Wärmeversorgung von Kommunen mit Wärmenetzen. Technical report, 2019. URL www.solites.de.

A. Grunwald. Diverging pathways to overcoming the environmental crisis: A critique of eco-modernism from a technology assessment perspective. *Journal of Cleaner Production*, 197: 1854–1862, 2018. ISSN 09596526. do: 10.1016/j.jclepro.2016.07.212. URL https://doi.org/10.1016/j.jclepro.2016.07.212.

J.-C. Hadorn. Solar and Heat Pump Systems. (September), 2010.

L. Hamelin, M. Borzęcka, M. Kozak, and R. Pudełko. A spatial approach to bioeconomy: Quantifying the residual biomass potential in the EU-27. *Renewable and Sustainable Energy Reviews*, 100(September 2017):127–142, 2019. ISSN 18790690. do: 10.1016/j.rser.2018.10.017.

K. Hansen and B. Vad Mathiesen. Comprehensive assessment of the role and potential for solar thermal in future energy systems. *Solar Energy*, 169(April):144–152, 2018. ISSN 0038092X. do: 10.1016/j.solener.2018.04.039. URL https://doi.org/10.1016/j.solener.2018.04.039.

Hotmaps Project. Hotmaps Project - The open source mapping and planning tool for heating and cooling. (Accessed: 2020-05-26). URL https://www.hotmaps-project.eu/.

IBEG e.V. ibeg - Definition Bioenergiedorf. (Accessed: 2020-04-17). URL http://www.bioenergiedorf.info/index.php?id=134.

IBEG e.V. ibeg - Die Jühnder Erklärung, 2015. URL http://www.bioenergiedorf.info/index.php?id=157.

I. Illich. Energy and equity. *The Environmentalist*, 1(3):246, 1981. ISSN 02511088. do: 10.1007/BF02233125.

T. Jackson. *Prosperity Without Growth ?*, volume 14. 2009. ISBN 1844078949. do: 10.1111/j.1530-9290.2009.00213.x.

T. Jenssen, A. König, and L. Eltrop. Bioenergy villages in Germany: Bringing a low carbon energy supply for rural areas into practice. *Renewable Energy*, 61:74–80, 2014. ISSN 09601481. do: 10.1016/j.renene.2012.08.014.

A. Jering, A. Klatt, J. Seven, K. Ehlers, J. Günther, A. Ostermeier, and L. Mönch. Globale Landflächen und Biomasse - nachhaltig und resourcenschonend nutzen. Technical report.

G. Kallis. In defence of degrowth. *Ecological Economics*, 70(5):873–880, 2011. ISSN 0921-8009. do: 10.1016/j.ecolecon.2010.12.007. URL `http://dx.doi.org/10.1016/j.ecolecon.2010.12.007`.

C. Kerschner, P. Wächter, L. Nierling, and M. H. Ehlers. Degrowth and Technology: Towards feasible, viable, appropriate and convivial imaginaries. *Journal of Cleaner Production*, 197: 1619–1636, 2018. ISSN 09596526. do: 10.1016/j.jclepro.2018.07.147.

KfW and BMWi. Erneuerbare Energien – Premium | gefördert von KfW und BMWi. (Accessed: 2020-04-28), 2019. URL `https://www.kfw.de/inlandsfoerderung/Unternehmen/Energie-Umwelt/Finanzierungsangebote/Erneuerbare-Energien-Premium-(271-281)/`.

E. Kiderlen, S. Ditrich, A. Wischnewski, R. Fücks, A. Poltermann, D. Landgrebe, U. Brümmer, and A. Maennel. *Grenzen des Wachstums - Wachstum der Grenzen*. Number 2. 2011. ISBN 9783869280479.

KIT - ITAS. KIT - ITAS - Staff - Armin Grunwald. (Accessed: 2020-02-13). URL `https://www.itas.kit.edu/english/staff_grunwald_armin.php`.

Kommunal Erneuerbar. Senftenberg - Kommunal Erneuerbar. (Accessed: 2020-04-13), 2016. URL `http://www.kommunal-erneuerbar.de/de/energie-kommunen/energie-kommunen/senftenberg.html`.

C. S. Kraan. D7.2a - Market analysis of heat , electricity and biofuels. Technical Report November, 2015.

C. Kunz and S. Kirrmann. Die Neue Wärmewelt - Szenario für eine 100% Erneuerbare Wärmeversorgung in Deutschland. Technical report, 2016. URL `https://www.unendlich-viel-energie.de/media/file/551.AEE_Neue_Waermewelt_Online.pdf`.

Landesanstalt Umwelt BaWü. SOLNET.BW-Solare Wärmenetze Baden-Wuerttemberg. (Accessed: 2020-04-29). URL `http://fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/121212/?COMMAND=DisplayBericht&FIS=203&OBJECT=121212&MODE=METADATA`.

S. V. Larsen, A. M. Hansen, and H. N. Nielsen. The role of EIA and weak assessments of social impacts in conflicts over implementation of renewable energy policies. *Energy Policy*, 115(April):43–53, 2018. ISSN 03014215. do: 10.1016/j.enpol.2018.01.002. URL `https://doi.org/10.1016/j.enpol.2018.01.002`.

R. A. Lee and J.-M. Lavoie. From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. *Animal Frontiers*, 3(2):6–11, 2013. ISSN 2160-6056. do: 10.2527/af.2013-0010.

R. Lindsey and L. Dahlman. Climate Change: Global Temperature | NOAA Climate.gov. (Accessed: 2020-05-25), 2020. URL `https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature`.

G. Longley and R. Maguire. *Geographic Information Systems and Science*. John Willey & Sons., 3rd editio edition, 2001.

V. Lottner, M. E. Schulz, and E. Hahne. Solar-assisted district heating plants: Status of the German programme Solarthermie-2000. *Solar Energy*, 69(6):449–459, 2000. ISSN 0038092X. do: 10.1016/S0038-092X(00)00125-0.

H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, and B. V. Mathiesen. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy*, 68:1–11, 2014. ISSN 03605442. do: 10.1016/j.energy.2014.02.089. URL `http://dx.doi.org/10.1016/j.energy.2014.02.089`.

D. H. Meadows, D. L. Meadows, J. Randers, and W. W. Behrens. *The Limits to Grow*. 1972. ISBN 0876631650. do: 10.1111/j.1752-1688.1972.tb05230.x.

B. Möller, E. Wiechers, U. Persson, L. Grundahl, and D. Connolly. Heat Roadmap Europe: Identifying local heat demand and supply areas with a European thermal atlas. *Energy*, 158: 281–292, 2018. ISSN 03605442. do: 10.1016/j.energy.2018.06.025.

S. Paardekooper, R. S. Lund, B. V. Mathiesen, M. A. C. Ojeda, U. R. Petersen, L. Grundahl, A. David, J. Dahlbæk, I. A. Kapetanakis, H. Lund, N. Bertelsen, K. Hansen, D. W. Drysdale, and U. Persson. Heat Roadmap Germany. 2018. URL `https://vbn.aau.dk/en/publications/be21f3ed-efc7-4efa-8358-4385a852fc3a`.

T. Pauschinger, P. Geiger, C. Winterscheid, H. Huther, and M. Sandrock. Solare Wärmenetze - Marktstatus 2018 für Deutschland und Europa. Technical Report 2, 2019a. URL `https://www.haustec.de/sites/default/files/2019-06/infoblatt_solare-waemenetze.pdf`.

T. Pauschinger, P. Geiger, C. Winterscheid, H. Huther, and M. Sandrock. Solare Wärmenetze. Technical Report 2, 2019b.

U. Persson, B. Möller, and S. Werner. Heat Roadmap Europe: Identifying strategic heat synergy regions. *Energy Policy*, 74(C):663–681, 2014. ISSN 03014215. do: 10.1016/j.enpol.2014.07.015.

Peta4. Peta4 – Heat Roadmap Europe. (Accessed: 2020-05-19). URL `https://heatroadmap.eu/peta4/`.

S. Pezzutto, S. Zambotti, S. Croce, P. Zambelli, G. Garegnani, C. Scaramuzzino, R. P. Pascuas, A. Zubaryeva, F. Haas, D. E. Exner, A. e. Müller, M. Hartner (TUW), T. Fleiter, A. Klingler, M. Kühnbach, P. Manz, S. Marwitz, M. Rehfeldt, J. Steinbach, and E. I. Popovski. Hotmaps Project, D2.3 WP2 Report – Open Data Set for the EU28, 2018. URL `https://gitlab.com/hotmaps/potential/potential_forest/-/blob/master/README.md`.

PlanEnergi. Solar Thermal Energy in Marstal – PlanEnergi. (Accessed: 2020-04-14). URL `http://planenergi.eu/activities/district-heating/seasonal-heat-storage/solar-thermal-energy-in-marstal/`.

PlanEnergi and NIRAS. Zahlen & Daten - Dronninglund. (Accessed: 2020-04-13). URL `https://www.waermepumpe.de/presse/zahlen-daten/`.

M. Rämä and S. Mohammadi. Comparison of distributed and centralised integration of solar heat in a district heating system. *Energy*, 137:649–660, 2017. ISSN 03605442. do: 10.1016/j.energy.2017.03.115.

J. Rommel, J. Radtke, G. von Jorck, F. Mey, and Yildiz. Community renewable energy at a crossroads: A think piece on degrowth, technology, and the democratization of the German energy system. *Journal of Cleaner Production*, 197:1746–1753, 2018. ISSN 09596526. do: 10.1016/j.jclepro.2016.11.114.

W. Schulz. Dekarbonisierung der fernwärme. (April), 2016. URL `https://www.agora-energiewende.de/fileadmin2/Projekte/2015/Sektorkopplung/05_Schulz_Praesentation_BET_13042016.pdf`.

SOLAR KEYMARK. SOLAR KEYMARK - solar thermal collector licences. (Accessed: 2020-05-20). URL `http://www.solarkeymark.nl/DBF/`.

Solarthermie.net. Pelletheizung & Solar - Klimaneutral heizen. (Accessed: 2020-04-29), a. URL `https://www.solarthermie.net/kombination/pelletheizung`.

Solarthermie.net. Wärmepumpen mit Solar erhöhen die Effizienz. (Accessed: 2020-04-29), b. URL `https://www.solarthermie.net/kombination/waermepumpe`.

P. A. Sørensen, J. E. Nielsen, R. Battisti, T. Schmidt, and D. Trier. Solar district heating guidelines: Collection of fact sheets. Technical Report August, 2012. URL `http://solar-district-heating.eu/Portals/0/Factsheets/SDH-WP3-D31-D32_August2012.pdf`.

Stadtwerke Ludwigsburg-Kornwestheim. Kommunales Klimaschutz-Modellprojekt SolarHeatGrid. (Accessed: 2020-04-17), 2020. URL `https://www.swlb.de/solar-heat-grid`.

H. Stocker. Energie aus Biomasse Teil 1 von 5, Biogas und Bioöl für die Energiewende - YouTube. (Accessed: 2020-04-12), 2015. URL `https://www.youtube.com/watch?v=V_IUaJcLY5A`.

S. Theuerl, C. Herrmann, M. Heiermann, P. Grundmann, N. Landwehr, U. Kreidenweis, and A. Prochnow. *The future agricultural biogas plant in Germany: A vision*, volume 12. 2019. ISBN 4933156999. do: 10.3390/en12030396.

Thinkbelt. Limits. (Accessed: 2020-02-13), 2019. URL https://thinkbelt.org/shows/interstitial/limits-giorgos-kallis.

trend:research/Leuphana and U. Lüneburg. Definition und Marktanalyse von Bürgerenergie in Deutschland. page 76, 2013. URL http://www.leuphana.de/fileadmin/user_upload/Forschungseinrichtungen/professuren/finanzierung-finanzwirtschaft/files/Definition-und-Marktanalyse-von-Buergerenergie-in-Deutschland.pdf.

V. Tulus, M. H. Abokersh, L. F. Cabeza, M. Vallès, L. Jiménez, and D. Boer. Economic and environmental potential for solar assisted central heating plants in the EU residential sector: Contribution to the 2030 climate and energy EU agenda. *Applied Energy*, 236(November 2018):318–339, 2019. ISSN 03062619. do: 10.1016/j.apenergy.2018.11.094. URL https://doi.org/10.1016/j.apenergy.2018.11.094.

Umwelbundesamt. Erneuerbare-Energien-Gesetz | Umweltbundesamt. (Accessed: 2020-04-27), 2019. URL https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-gesetz#erfolg.

Umweltbundesamt. Bioenergie. (Accessed: 2020-04-12). URL https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/bioenergie#iLUC.

Umweltbundesamt. Globale Landflächen und Biomasse -nachhaltig und resourccenschonend nutzen. Technical report, 2019.

Umweltbundesamt. Erneuerbare Energien in Deutschland - Daten zur Entwicklung 2019. Technical report, 2020. URL https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-03-13_hgp-ee-in-zahlen_online.pdf.

Viessmann GmbH. Projektskizze „ Sonnen - und Bioenergiedorf Mengsberg “ Die Viessmann Group Familienunternehmen mit Stammsitz in Allendorf. Technical report, 2020a. URL https://www.viessmann.de/de/kommunen/bioenergiedorf.html.

Viessmann GmbH. Projektskizze „ Nahwärmeversorgung Moosach “ Ein Projekt der NATURSTROM AG Die Viessmann Group. pages 1–18, 2020b. URL https://www.viessmann.de/de/kommunen/bioenergiedorf.html.

J. Vishnupriyan and P. S. Manoharan. Multi-criteria decision analysis for renewable energy integration: A southern India focus. *Renewable Energy*, 121:474–488, 2018. ISSN 18790682. do: 10.1016/j.renene.2018.01.008. URL https://doi.org/10.1016/j.renene.2018.01.008.

K. Volkart, N. Weidmann, C. Bauer, and S. Hirschberg. Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland. *Energy Policy*, 106 (February):155–168, 2017. ISSN 03014215. do: 10.1016/j.enpol.2017.03.026. URL http://dx.doi.org/10.1016/j.enpol.2017.03.026.

C. Von Bock Und Polach, C. Kunze, O. Maaß, and P. Grundmann. Bioenergy as a socio-technical system: The nexus of rules, social capital and cooperation in the development of bioenergy villages in Germany. *Energy Research and Social Science*, 6:128–135, 2015. ISSN 22146296. do: 10.1016/j.erss.2015.02.003.

WDR. Nordrhein-Westfalen: Friedlicher Protest gegen Datteln 4 | tagesschau.de. (Accessed: 2020-05-31), 2020. URL `https://www.tagesschau.de/regional/nordrheinwestfalen/protest-datteln-101.html`.

J. Weber, B. Ganz, B. Sanner, and I. Moeck. Geothermal Energy Use , Country Update for Germany. *European Geothermal Congress*, (June):3–7, 2013.

I. Wilkens and P. Schmuck. Transdisciplinary evaluation of energy scenarios for a German village using multi-criteria decision analysis. *Sustainability*, 4(4):604–629, 2012. ISSN 20711050. do: 10.3390/su4040604.

J. Xue. Is eco-village/urban village the future of a degrowth society? An urban planner's perspective. *Ecological Economics*, 105:130–138, 2014. ISSN 09218009. do: 10.1016/j.ecolecon.2014.06.003. URL `http://dx.doi.org/10.1016/j.ecolecon.2014.06.003`.

Appendices

Appendix A: Processing Data with Q-GIS / PostGIS

Processing and merging the data of the district level (NUTS3) (a,b,c) with the data spots (i,ii,iii) another GIS software was utilized - PostGIS. The residue layers (a, b, c) are in a NUTS3-format (district-sharp resolution of Europa-28) areas and have the format of polygons, which have the discrete forms of the districts (NUTS3) illustrated in the map in Figure 6.1 as 'nutse'. These NUTS3-layers contain the information of the residue types a),b), c) as depicted in Table 6.1. The data is processed and merged in three steps. In a first step (see 1-step in A the vector point layer containing the locations of the BED get a 'buffered circle' of 50 km radius. This buffered BED is than intersected with the residue layers to obtain the relative amount of intersecting area.

```
#1-step#
SELECT, B.id, B.name, B.geom, N.forest, N.agriculture, N.livestock,
ST_Area(ST_Intersection(N.geom, ST_Buffer(B.geom, 50000))) / ST_Area(N.geom) AS perc_area
INTO bio_cities_nutse_intersection FROM nutse AS N, bio_cities AS B
WHERE ST_Area(ST_Intersection(N.geom, ST_Buffer(B.geom, 50000))) / ST_Area(N.geom) > 0

#2-step#
SELECT id, name, perc_area, forest * perc_area AS forest_bed, agriculture * perc_area AS agriculture_bed, livestock * perc_area AS,
livestock_bed, geom
INTO bio_cities_nutse_intersection_multiplied FROM bio_cities_nutse_intersection

#3-step#
SELECT, id, name, SUM(forest_bed) AS aggregated_forest, SUM(agriculture_bed) AS aggregated_agriculture, SUM(livestock_bed) AS
aggregated_livestock,
geom INTO bio_cities_nutse_aggregated FROM bio_cities_nutse_intersection_multiplied GROUP BY id, name, geom
```

Figure A: Query or command code that merges the district biomass potential residue data with a buffer of a 50 km radius around the coordinates of the BED and pBED

In a second step, these calculated intersections are multiplied with the residue energy value (in PJ) with the relative share of the intersection calculated in the step above. In a third and final step, the energy values (in PJ) are summed up to one final value for each (i) BED, respectively (ii) pBED and for each residue type (a,b,c). [Note: Supported by Niels Bach-Sørensen]

Appendix B: Interview Partners

(i-1) Dr. Hansen - Fachagentur nachwachsende Rohstoffe
Dr. Hansen works in public relation for bioenergy at FNR. He is specialized in heating with wood, bio-fuels and further responsible for the BED-competition and the Bio-Energy-Villages (now: Bioenergy-Communities), further he is responsible for the BED-homepage of the FNR, that depicts a map of BED and further technical information for other interested villages. The FNR and he are not competitors of any engineering consultants.

(i-2) Dr. Westholm - Hamburg Institut
Dr. Westholm has been working for 7 years at Hamburg Institute, that is primarily a consultancy for the German ‚Energiewende‘. He is social scientist working as political sociologist and in environmental politics.. At Hamburg Institut he works on policy control instruments that can help federal governments to enhance concepts in climate protection especially focusing the heat transition in Germany. His last project was an accompanying research project for the SolnetBW program of Germany's south-wester federal state Baden-Württemberg.

(i-3) M. Rudewig - BED Mengsberg, electrical engineer
M. Rudewig is electrical engineer from Mensberg, he planned 50 wind turbines and is operating them and in the managing board of the cooperative Mengsberg that planned the DH supplied by a STS and BM boilers.

(i-4) H. Gröbmeyer - BED Moosach, Climate Protection - Manager 34 years as teacher at professional school, lastly director of a professional school for construction, knows heating concepts for building areas also from the municipal council, climate-protection manager from Ebersberg where he founded an energy agency (today: 20 staff), founding energy cooperative: citizen energy, together with communes, a local community organization that bought the electricity grid of the county

(i-5) Hr. Dürr-Pucher - lobbyist at RES plattform BW
Self-employed, project-development company: clean-energy, Leader of project development of Solarcomplex AG: department BED, Public relations in city councils, lobbyist at RES plattform BW (wind, pv, DH); involved in BED Mauenheim, first BED in BW with BG-boiler in 2005 in which Solarcomplex AG partnered.

(i-6) Bene Müller – Management Board Solarcomplex AG
Bene Müller, is one out of 20 founders of the ‚Solarcomplex AG‘ and today in the managing board.. In total the combination of SDH and BM has been built three times. Currently, two projects are being built (Häusern, Jungnau).

(i-7) G. Brandt - BED Jühnde, Management Board
He did not revision the notes.