HELMHOLTZ
Centre for Environmental Research

Matthias Jordan

The future role of bioenergy in the German heat sector: Insights from an energy system analysis

PHD DISSERTATION 13|2021
Helmholtz Centre for Environmental Research – UFZ
Department of Bioenergy

The future role of bioenergy in the German heat sector: Insights from an energy system analysis

A DISSERTATION

Approved by the Faculty of Economics and Management Science,
Leipzig University,

for Obtaining the Academic Degree

Doktor-Ingenieur
Dr.-Ing.

Presented

by Dipl.-Ing. Matthias Jordan
born on 22 June 1982 in Erfurt, Germany

Reviewers:

Prof. Dr.-Ing. Daniela Thrän
Jun.-Prof. Dr. Paul Lehmann

Date of conferral:
08 December 2021

Bibliographic description

Jordan, Matthias

The future role of bioenergy in the German heat sector: Insights from an energy system analysis:

Leipzig University, dissertation
XIV+93 pp., 236 ref., 31 figures, 13 tab., 4 annexes

Abstract:

Global climate change requires a transition of the energy system towards renewable solutions. The transformation in the German heat sector, responsible for over half of the final energy consumption in Germany, is stagnating and requires various individual solutions in a heterogeneous market. Besides varying technological requirements, various stakeholders with different interests influence the market development. Bioenergy delivers the major share of only 14% renewable heat today. In the future, this distribution is expected to change and the future role of bioenergy is uncertain. Biomass is limited and in competition between different usage options. Consequently, the sustainable utilization of the limited biomass potential in an efficient, cost optimal way is the challenge we are facing today.

Addressing this research gap, an energy system optimization model (ESOM) was set up. A focus is set on a detailed representation of the various technological bioenergy options and the heterogeneous heat sector under consideration of consumer choice and future uncertainties. Besides several scenario analysis, a comprehensive sensitivity analysis was conducted to determine the influence of uncertainties and identify robust solutions.

Through the outlined method, it is found that solid biomass, in the form of either wood chips, pellets, log wood or Miscanthus chips, is in all investigated cases a competitive option to fulfill the defined climate targets. Especially, the use of wood chips from residues and Miscanthus in high temperature industry applications is identified as the most robust option under all investigated uncertainties from a systems perspective. In these applications, renewable alternatives are rare and renewable power can more efficiently be used in other heat sub-sectors.

Additionally, log wood technologies in the private household sector are found to be a competitive option, especially when consumer behavior is considered. However, this finding does not apply to houses with high insulation standards, in which economic factors are found to be predominant. Furthermore, hybrid CHP pellet systems are found to be a competitive option under the assumption of strongly increasing power prices. However, increasing power prices a likely to decelerate the heat transition as they lead to an economic advantage of natural gas technologies compared to power based renewable heat supply. Besides the power price, the future gas price development and the consideration of consumer behavior are identified as significantly influential on the future use of bioenergy.

With the outlined thesis, novel methodological approaches are introduced, contributing to both, the uncertainty assessment in energy system analysis and the integration of consumer choice in ESOMs. The performed analyses in this thesis investigate a wide range of solutions and provide policy insights with a high level of confidence.

Declaration of academic integrity

I hereby declare that I have composed this dissertation myself and without inadmissible outside help, in particular without the help of a doctoral consultant (Promotionsberater). I have used no other sources and aids than those stated. I have indicated all text passages that are incorporated, verbatim or in substance, from published or unpublished writings. I have indicated all data or information that is based on oral communication. All material or services provided by other persons are indicated as such.

I hereby declare that the submitted dissertation has not been submitted, either in whole or in part, either in Germany or abroad in the same or a similar form to an examination office for the purpose of a doctorate or other examination procedure.

I hereby declare that I accept the doctoral regulations of the Faculty of Economic Sciences of the University of Leipzig, dated 06 October 2020.

Leipzig, 25 January 2021

Matthias Jordan

Abstract

Global climate change requires a transition of the energy system towards renewable solutions. The transformation in the German heat sector, responsible for over half of the final energy consumption in Germany, is stagnating and requires various individual solutions in a heterogeneous market. Besides varying technological requirements, various stakeholders with different interests influence the market development. Bioenergy delivers the major share of only 14% renewable heat today. In the future, this distribution is expected to change and the future role of bioenergy is uncertain. Biomass is limited and in competition between different usage options. Consequently, the sustainable utilization of the limited biomass potential in an efficient, cost optimal way is the challenge we are facing today.

Addressing this research gap, an energy system optimization model (ESOM) was set up. A focus is set on a detailed representation of the various technological bioenergy options and the heterogeneous heat sector under consideration of consumer choice and future uncertainties. Besides several scenario analysis, a comprehensive sensitivity analysis was conducted to determine the influence of uncertainties and identify robust solutions.

Through the outlined method, it is found that solid biomass, in the form of either wood chips, pellets, log wood or Miscanthus chips, is in all investigated cases a competitive option to fulfill the defined climate targets. Especially, the use of wood chips from residues and Miscanthus in high temperature industry applications is identified as the most robust option under all investigated uncertainties from a systems perspective. In these applications, renewable alternatives are rare and renewable power can more efficiently be used in other heat sub-sectors.

Additionally, log wood technologies in the private household sector are found to be a competitive option, especially when consumer behavior is considered. However, this finding does not apply to houses with high insulation standards, in which economic factors are found to be predominant. Furthermore, hybrid CHP pellet systems are found to be a competitive option under the assumption of strongly increasing power prices. However, increasing power prices a likely to decelerate the heat transition as they lead to an economic advantage of natural gas technologies compared to power based renewable heat supply. Besides the power price, the future gas price development and the consideration of consumer behavior are identified as significantly influential on the future use of bioenergy.

With the outlined thesis, novel methodological approaches are introduced, contributing to both, the uncertainty assessment in energy system analysis and the integration of consumer choice in ESOMs. The performed analyses in this thesis investigate a wide range of solutions and provide policy insights with a high level of confidence.

Keywords: heat sector; bioenergy; optimization; uncertainty assessment; consumer behavior.

Acknowledgements

First of all thank you to Daniela Thrän and Markus Millinger for giving me the opportunity and trust to do this. For me personally, you have been the ideal combination of supervisors. Thank you for giving me the freedom to develop my own ideas, for the constructive discussions we had and the flexibility I needed for my work-family balance. Markus, thank you for the great and interesting time we had in the past years working on the modeling, projects and spending time on conferences.

A special thank you also to Volker Lenz for the fruitful discussions on the modeling and the results. Thank you also for preparing the technology data base, which has been fundamental for this work. Raik Becker, thank you for the countless discussions on the modeling details we had as office mates in the first years.

Thank you also, to everybody past and present in my working environment at the UFZ and DBFZ, especially and in no particular order: Frazer Musonda, Michael Steubing, Maik Budzinski, Katja Bunzel, Reinhold Lehneis, David Manske, Katrina Chan, Helen Kollai, Björn Schinkel, Caroline Lichtmann, Claudia Klötzing, Katja Oehmichen, Stefan Majer, Alberto Bezama, André Brosowski, Henryk Haufe, Nora Szarka, Julian Rode, Charlotte Hopfe, Juliana Mai, Klaus Hennenberg, Anneliese Koppelt and everybody I forgot.

Thank you to my parents Jürgen and Corina for everything you provided for me. Thank you Mareike, Moritz and Tim for being so supportive and patience.

Matthias Jordan

Leipzig, January 2021

List of Publications

This thesis is based on the following appended papers:

I Jordan, M., Lenz, V., Millinger, M., Oehmichen, K. and Thrän, D. (2019) *Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach.* Energy. 189, art. 116194.

II Jordan, M., Millinger, M. and Thrän, D. (2020) *Robust bioenergy technologies for the German heat transition: A novel approach combining optimization modeling with Sobol' sensitivity analysis.* Applied Energy. 262, art. 114534.

III Jordan, M., Hopfe, C., Millinger, M., Rode, J. and Thrän, D. (2021) *Incorporating consumer choice into an optimization model for the German heat sector: Effects on projected bioenergy use.* Journal of Cleaner Production. 295 , art. 126319.

IV Jordan, M., Millinger, M. and Thrän, D. (submitted) *Benopt-Heat: An economic optimization model to identify robust bioenergy technologies for the German heat transition.*

Work related to this thesis has also been presented in the following publications:

Lenz, V., Szarka, N., **Jordan, M.**, Thrän, D. (2020). *Status and perspectives of biomass use for industrial process heat for industrialized countries, with emphasis on Germany.* Chem. Eng. Technol. 43 (8), 1469 - 1484.

Jordan, M., Lenz, V., Millinger, M., Oehmichen, K., Thrän, D. (2019). *Competitive biomass key applications to fulfill climate targets in the German heat sector: Findings from optimization modelling.* 27th European Biomass Conference: Setting the course for a biobased economy. Proceedings of the International Conference held in Lisbon, Portugal, 27-30 May 2019, ETA-Florence Renewable Energies, Florence, p. 1801 - 1803.

Jordan, M., Lenz, V., Oehmichen, K., Haufe, H., Millinger, M., Szarka, N., Majer, S., Thraen, D., Schüngel, J., Schaldach, R. (2019). *Bioplan W: Systemlösungen Bioenergie im Wärmesektor im Kontext zukünftiger Entwicklungen.* Bioenergie: Der X-Factor! 8. Statuskonferenz Reader energetische Biomassenutzung, 17. - 18. September 2019, Leipzig, DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig, S. 44 - 45.

Thrän, D., Szarka, N., Haufe, H., Lenz, V., Majer, S., Oehmichen, K., **Jordan, M.**, Millinger, M., Schaldach, R., Schüngel, J. (2020). *BioplanW: Systemlösungen Bioenergie im Wärmesektor im Kontext zukünftiger Entwicklungen. Schlussbericht.* DBFZ Report 36, DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig, 81 S.

Thrän, D., Lauer, M., Dotzauer, M., Kalcher, J., Oehmichen, K., Majer, S., Millinger, M., **Jordan, M.**(2019). *Technoökonomische Analyse und Transformationspfade des energetischen Biomassepotentials (TATBIO) : Endbericht zu FKZ 03MAP362.* DBFZ Deutsches

Biomasseforschungszentrum gemeinnützige GmbH, Leipzig, 130 S.

List of Acronyms

AMS	–	Ambitious Measures Scenario
BAU	–	Business As Usual
BECCS	–	BioEnergy Carbon Capture and Storage
CHP	–	Combined Heat and Power
CO_2	–	Carbon dioxide
DH	–	District Heating
ESOM	–	Energy System Optimization Model
GHG	–	GreenHouse Gas
HP	–	Heat Pump
Ind	–	Industry
M.E.	–	Marginal Effect
SFH	–	Single Family House
SRC	–	Short Rotation Coppice
ST	–	Solar Thermal
PH	–	Private Household
PV	–	PhotoVoltaic

Contents

Part I

Introductory chapters

Chapter 1

Background

Global climate change, caused by man-made emissions, affects all nations and requires a transition of national energy systems away from fossil fuels to renewable solutions. In Germany, ambitious emission reduction and efficiency improvement targets are defined by the government [9]: by 2050, greenhouse gas (GHG) emissions in the energy sector are to be reduced by 80-95% compared to 1990 levels. Considering the European green deal from 2020, a minimum target of 95% GHG reduction needs to be pursued. A major share of that reduction needs to be covered by the heat sector, which accounts for $\sim 35\%$ of the energy based emissions [51], and $\sim 53\%$ of the final end energy demand [10] in Germany today. Meeting the defined reduction targets is only possible by switching to renewable technologies in the heat sector and at the same time reducing demand by increasing the refurbishment measures. The heat sector is a heterogeneous market in terms of applications, infrastructures, demand profiles and also stakeholders. In the last ten years, the transition towards renewable heat supply was stagnating. Today, only 14,5% of the heat supply is renewable and a large proportion of that is provided by bioenergy (87%) [50]. This picture needs to change in the next decades to achieve the defined climate protection targets. Policy makers in Germany are now acting by increasing subsidies for renewable heat investments starting in 2020 and introducing a CO_2 price for heat from 2021. However, the future role of bioenergy in the German heat sector is unclear, and policy makers need clear recommendations on how to efficiently allocate the limited biomass potential between energy, chemical, and material uses, and also within the heterogeneous heat sector.

The resource biomass is limited and a great share of the German yearly usable potential is already exploited [7]. Today, the biomass used for heating is mostly in solid form (77%) [50], the major share in classic small combustion plants in private households, with potentially high particulate matter emissions [5]. The applications for solid biomass range from wood fired stoves over pellet stoves to combined heat and power (CHP) plants supplying district heating systems. Additionally, 22% are used from digestible biomass in the form of biogas [50]. Only 1% is used in liquid form. The role of biomass for the future use in renewable technologies is hotly debated today. For example, there is the food versus fuel debate if stemming from cultivation. Land use for biomass production is in competition between different usage options, as e.g. food, feeding, energy, material, biodiversity or recreation space and therefore the cultivaton of biomass can lead to direct or indirect land use change with negative effects [25]. However, bioenergy from residues even has ecologically beneficial side effects in some cases. For example, the fermentation of manure not only provides energy, but also reduces GHG emissions and converts the manure into a fertilizer that is more compatible with the soil [5]. From a systems perspective, bioenergy has some clear advantages compared to other renewable fluctuating energy sources to supplement the energy supply from wind and PV, such as e.g. weather independency, the possibility of simple storage and flexible utilization [48]. These properties open up a wide field of applications for biomass within the different sub-sectors of the heat sector. Consequently, the sustainable utilization of the limited biomass from residues and cultivation in an efficient, cost optimal way is the challenge we are facing today.

1.1 The complexity of the German heat sector

In Germany, heat consumption takes place in millions of residential buildings ($\sim$ 43% of the German final heat demand of 4864 PJ), trade and commerce buildings ($\sim$ 17%), as well as in many different fields of the industry ($\sim$ 40%), mostly the steel and chemical industries [1]. Within these markets different demand structures occur, ranging from seasonal demand for space heating, daily fluctuating demand for hot water to constant demand for processes in the industry. Most of the heat is produced at the location it is required, additionally 400-450 PJ/a are distributed via district heating grids, mostly to residential buildings ($\sim$ 38%) or the industry ($\sim$ 43%) [10]. From over 32 Mio heating systems installed [3], $\sim$ 12 Mio are bioenergy heating systems [3, 41], supplying the major share of renewable heating. Beside a large refurbishment potential to increase energy efficiency in buildings, the heat transition needs several renewable technological solutions for a complex market with diverse demand structures. For this purpose, technologies must be available in a wide variety of system sizes for a wide range of building types and industrial applications.

Within the heat sector a broad variety of heat provision options exist, see Table 1.1. Renewable alternatives to bioenergy are e.g. heat pumps, solar thermal or the use of geothermal energy. Heat pumps, using e.g. ambient heat, are a promising technology having a high potential to reduce GHG emissions as long as the required input in form of electricity is produced out of high shares of renewable technologies. Solar thermal also has a high potential for GHG reduction. But in Germany, this technology requires an additional heat source or adequate seasonal storage in order to be able to supply heat also in winter [14]. Another alternative is geothermal energy. The use of this energy form is linked with high investment costs and therefore only economically viable for plants of sizes in the MW range. Additionally, the distribution of geothermal energy requires a district heating grid. In 2015, 26 plants were installed in Germany and 45 plants were in the planning [14]. The use of industrial waste heat has a high potential with approx. 813 PJ unused heat from different industry sectors and temperature levels [14]. Barriers for exploiting this waste heat are high investment costs required for individual solutions. Another key component in the future heat sector could be thermal storages. They can be combined with several technologies in a variety of sizes from daily storages to seasonal storages and therefore contribute to the flexibility of the combined technologies. All power based technologies are directly connected to the power sector and, if considering supply and demand as well, indirectly connected to the development of the transport sector (electric mobility).

The heat transition is not only from a technical view characterized by its heterogeneity. The heat transition is influenced by a variety of economic, ecological, social and organisational drivers and barriers. Various stakeholders as owners and operators with

Table 1.1: Share of different heat provision types in the German heat sector in 2019 [1, 50].

	Absolut in PJ	**Share in %**
Biogenic solid fuels (households)	247,7	5,1%
Biogenic solid fuels (trade and commerce)	63,5	1,3%
Biogenic solid fuels (industries)	85,7	1,8%
Biogenic solid fuels (district heating)	20,3	0,4%
Biogenic liquid fuels	8,3	0,2%
Biogenic gaseous fuels	69,2	1,4%
Biogenic content of the waste	52,1	1,1%
Solar thermal	30,5	0,6%
Deep geothermal energy	4,4	0,1%
Near-surface geothermal energy, ambient heat	52,7	1,1%
Coal	418,1	8,6%
Mineral oils	765,6	15,7%
Natural gas	2149,6	44,2%
Electricity	434,3	8,9%
District heating	388,3	8,0%
Others	73,5	1,5%
Sum:	4863,8	100,0%

different interests, preferences and behavioral characteristics are in place. For instance, millions of homeowners in the private household sector make their own heating system investment decision. They have only limited information and are not able to fully understand the whole complex system. Hence, investment decisions can be influenced by many factors that deviate from the assumption of economic rationality [24, 13]. Renewable heat supply concepts have generally a local character and need to cover heterogenous requirement profiles. Systemic, trans-sectoral and participatory approaches are therefore needed to transfer the national energy transition goals to the local planning and implementation level. Ideally, planning should take place at the district level and the process organization is elemental to success. [14].

According to national energy scenarios in Germany, it is expected that in the transformation of the heat sector, major shares of renewable heat will be provided by heat pumps and solar thermal [40]. Additionally, a variety of individual, hybrid solutions will be required, depending on the regional conditions (e.g. geothermal potential, availability and economic feasibility of district heating) [14]. Bioenergy is expected to contribute to a cost effective, secure energy supply, be ecologically friendly and contribute to regional value creation [25]. Bioenergy should primarily take over those functions in the energy system that other renewable energy sources cannot fulfill or can only fulfill at very high costs [25]. An analysis of the major energy scenarios in Germany shows high shares of the limited biomass to be used in the heat sector [45]. The most important future areas of application in the heat sector are currently considered to be the provision of industrial heat, the flexible CHP generation and the combination of those applications with bioenergy carbon capture and storage (BECCS) [25]. However, major uncertainties exist in the current developed transformation pathways. Therefore regular and transparent reevaluations are recommended [25].

Due to the complexity of the demand structure in the heat sector, the manifold possibilities of technological concepts and the given limitations, uncertainties and other factors influencing future market development, the determination of the cost-optimal technology mix for the German heat transition is a complex issue. Especially the future role of bioenergy within this transition is attached with uncertainties. Energy system analysis using model based approaches are a common approach to tackle such issue.

1.2 Energy system analysis

For energy system analysis different approaches and model types are being used to inform climate policy. A common approach to model the competition of energy technologies in detail is to use bottom-up energy system optimization models (ESOM) [16, 21]. It is a classic approach widely used to model the system-wide impacts of energy development and suites the aims and objectives of this work [12].

On the German heat sector a variety of models were applied dealing with technological competition focusing on current prices and national regulations or specialized on particular technologies. Merkel et al. [34] focused on a decentralized heating model combined with a residential building stock simulation concentrating on fulfilling the policy targets under different scenarios. The study is exclusively considering the residential market and not the complete heat sector. The outcome of the optimization shows, that the future residential heat sector is dominated by heat pumps and solar irradiation. Biomass is only playing a minor role in the long term scenario. Merkel et al. [34] also did a comparison of in total 22 studies modeling the heat sector. Only three of those consider the complete heat sector in Germany, a time horizon until 2050 and an optimization approach. However, none of the mentioned studies is considering the wide range of bioenergy technologies available and the preliminary biomass conversion pathways. Especially technologies using biomass completely or partially as an energy source are not considered in detail.

Other models have a focus on the optimal distribution of biomass within the energy system. The future role of biomass in the power sector is investigated in various models, for example in combination with the district heating market of the heat sector [38] or to investigate the flexibility contribution of bioenergy [28]. Millinger et al. [36] model the competition in the transport sector with a focus on bioenergy technologies. With the same model the allocation of biomass over all German energy sectors was investigated [49]. The results show a robust demand for bioenergy in the heat sector, which was modeled only roughly in this study.

A major criticism of ESOMs is that the models are shaped by factors which are deeply uncertain [12], including e.g. technology innovation, resource availability, future feedstock price developments and socioeconomic dynamics. Yue et al. [52] reviewed over 2000 studies associated with ESOMs. The majority of them have been used in a deterministic fashion with limited attention paid to uncertainty. Only 34 studies performed a systematic uncertainty assessment. Moreover, behavioral aspects are identified to be the least understood dimension in optimization models and further methods to integrate scientific behavioral analysis are strived for [16]. Today, consumer choice is rarely integrated in ESOMs, especially for the heat sector.

In conclusion, a detailed study of the future use of bioenergy in the German heat sector has not yet been carried out. In particular, relevant aspects such as a detailed representation of the heterogeneous heat sector, the various biomass conversion options, social components and the consideration of uncertainties have not been taken into account in this context.

1.3 Aim and objectives

The aim of this work is to address the above identified research gap by assessing the future techno-economic potential of bioenergy within the German heat transition and to determine its cost optimal use under consideration of future uncertainties and the heterogeneity in technological structure and consumers.

For this purpose, an ESOM, based on an existing approach [37], is set up representing the heterogeneous heat sector with a variety of technological concepts, based on a detailed data basis. A special focus is on bioenergy technology concepts, to determine an efficient, cost optimal use of the limited biomass available. A comprehensive sensitivity assessment determines the influence of uncertainties and identifies robust solutions.

The objective of this thesis is to provide a wider basis for the design of an economically and environmentally friendly heat sector (bioenergy and other renewables) in Germany within the framework of the climate protection plan [9].

The following research questions are assessed within this thesis:

- Which bioenergy technology concepts are competitive options in a future, climate target fulfilling heat sector and how do their potential roles differ in different heat sub-sectors?
- Which uncertain factors have a significant influence on the future role of heat from biomass and which technology concepts are robust solutions based on these factors?
- Which model projections arise in the German heat sector under consideration of consumer choice in different scenarios?

The thesis consists of two parts. Part I is a general introduction to the field and puts the appended papers into context. Part II contains the appended papers. Some text fragments of the appended papers are quoted in the method chapters of part I.

Chapter 2

Methodology

2.1 Energy system optimization modeling

A best practice for energy system optimization modeling has been formalized by DeCarolis et al. [12], including a description of guiding principles for ESOM based analysis. Key steps associated with the application of ESOMs include: (1) Formulate research questions, (2) Set spatiotemporal boundaries (3), Consider model features (endogenous technical learning, lumpy investment, hurdle rates, consumer choice, price elastic demands, macroeconomic feedbacks), (4) Conduct and refine analysis, (5) Quantify uncertainty (scenario analysis, sensitivity analysis, stochastic optimization, near-optimal solutions), (6) Communicate insights.

The development of the ESOM in this thesis followed these guiding principles and the relevant key steps were conducted and are described in the following. First, the research questions were formulated, described in section 1.3. The spatial boundary was set to Germany as a whole, imports and exports are not considered, as a national solution for the limited biomass potential is searched for. The model time horizon was set to 2015-2050, according to the time frame of the national climate target. The temporal resolution is set to a yearly one. From the potential model features lumpy investment and consumer choice are considered and integrated into the model. Lumpy investment constrains the model to build discrete sizes of particular technologies, in this case representing a concrete heating system in a house or industry plant. Consumer choice is considered particularly important in this context, as millions of stakeholders in the heat sector make their own investment decisions, influenced by a variety of factors. The other potential model features were identified to be not purposeful for this investigation.

DeCarolis et al. [12] states the importance of uncertainty analysis, as the long-term future modeling of an energy system is shaped by a combination of factors that are deeply uncertain. In this thesis a strong focus is set on uncertainty assessments. Beside various scenario analyses, a comprehensive sensitivity analysis was conducted investigating a wide range of uncertainty. A systematic assessment can test the robustness of the model results by identifying which parameters drive the model outputs and help focus scenario analyses [12]. Based on these findings policy insights are communicated with a high level of confidence.

2.2 Model description

In order to model the competition between the technological options within the heat sector, an ESOM was developed. The model is fully deterministic and uses perfect foresight. It is a linear model, using the Cplex solver. As a programming environment GAMS [15] is used in combination with MATLAB [47]. The model structure is as follows, also described in Jordan et al. [22]: the three main sectors of the German heat sector, private household, industry and trade/ commerce are further divided into several sub-sectors, with different properties in terms of demand profiles and infrastructures. In total, 19 sub-sectors were defined and described: five sub-sectors for single-family houses (SFH), four for multi-family houses, five for the trade and commerce sector and five for the industry and district heating. The future development of the heat demand in buildings is based on the external results of the building stock model 'B-STar' [26], which models the future refurbishment of the German building stock in a yearly resolution using an agent based approach. Within the optimization model, for each sub-sector, representative bioenergy-, fossil- and other renewable (hybrid-) heat technology concepts are described and published in Lenz and Jordan [29], incl. e.g. gas boiler, heat pumps, direct electric heating, solar thermal, log wood, wood pellet and wood chip technologies. In total 23 biomass products (incl. wood based residues, log wood, straw, manure, two perennial crops and seven types of energy crops) and 3 fossil feedstocks are possible inputs [29]. For the single technology components, infrastructure emissions as well as the feedstock specific emissions are considered within the model. Fig. 2.1 shows the model architecture, also including the integration of the sensitivity analysis. The model consists of a user interface and six main modules. The six functions can be called from different applications such as the user interface, where scenario analysis can be customized. For a detailed description of the architecture and the functionalities, the user is refered to paper 4.

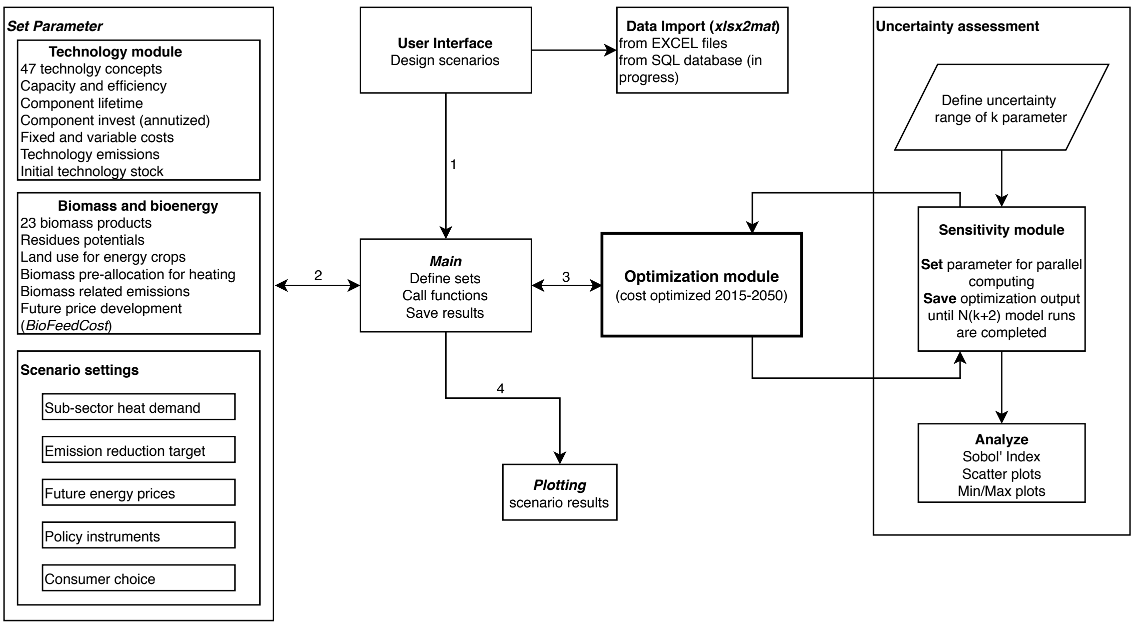

Figure 2.1: Model architecture schematic, see paper 4. Boxes represent modules and arrows represent data flow. The function names are written in italics. The numbers on the arrow show the order in which the functions are executed.

The objective function is minimizing the total system costs over all technologies i, all sub-sectors s and the complete timespan t=2015...2050 (2.1). The total system costs are the sum of the technology specific marginal costs mc, multiplied with the amount of heat produced π, and the investment costs ic, discounted with the annuity method (discount rate q) [20], multiplied with the number of heating systems installed n^{cap}. In the model each (hybrid-)heat-technology concept is separated into different modules j, assigned with different lifetimes $\hat{t}$ and individual investment costs.

Objective function

$$min \sum_{t,i,s,b} mc_{t,i,s,b} \cdot \pi_{t,i,s,b} + \sum_{t,i,j,s} ic_{t,i,j,s} \cdot n^{cap}_{t,i,j,s} \cdot \frac{q(1+q)^{\hat{t}_j}}{(1+q)^{\hat{t}_j}-1} \tag{2.1}$$

subject to

$$\delta_{t,s} = \sum_{i,b} \pi_{t,i,s,b}, \forall(t,i,s,b) \in (T,I,S,B) \tag{2.2}$$

$$\phi^{Res}_t + \Lambda^{Land}_t \cdot Y_{t,b} \geq \sum_{i,s,b} \dot{m}_{t,i,s,b}, \forall(t,i,s,b) \in (T,I,S,B_{bio}) \tag{2.3}$$

$$\varepsilon^{max}_t \geq \sum_{i,s,b} \alpha_{i,s} \cdot (\varepsilon^{rel}_{t,i,s} \cdot \pi_{t,i,s} + \varepsilon^{feed}_{t,i,s,b} \cdot \dot{m}_{t,i,s,b}), \forall(t,i,s,b) \in (T,I,S,B) \tag{2.4}$$

$$\pi_{t,i,s,b} = \dot{m}_{t,i,s,b} \cdot \eta_{t,i,s}, \forall(t,i,s,b) \in (T,I,S,B) \tag{2.5}$$

$$n^{cap}_{t=2015,i,j,s} = n^{initial}_{i,j,s}, \forall(t,i,j,s) \in (T,I,J,S) \tag{2.6}$$

$$n^{cap}_{t+1,i,j,s} = n^{cap}_{t,i,j,s} + n^{ext}_{t+1,i,j,s} - n^{dec}_{t+1,i,j,s}, \forall(t,i,j,s) \in (T,I,J,S) \tag{2.7}$$

$$n^{dec}_{t,i,j,s} = n^{initialdec}_{t,i,j,s} + n^{extdec}_{t,i,j,s}, \forall(t,i,j,s) \in (T,I,J,S) \tag{2.8}$$

$$n^{extdec}_{t+\hat{t}_j,i,j,s} = n^{ext}_{t,i,j,s}, \forall(t,i,j,s) \in (T,I,J,S) \tag{2.9}$$

Marginal costs include feedstock costs (fossil or biomass), costs for power demand, maintenance and a CO_2-certificate price. The sum of these costs has a dynamic development, which depends on the time point, used technology, sub-sector and if applicable the consumed feedstock product b. Generated power in a CHP system is included as a credit within the variable costs.

The main model restrictions are as follows:

- The heat demand δ in each sub-sector needs to be fulfilled. Therefore the sum of the produced heat within one sub-sector equals the heat demand within a sub-sector in each year (2.2).
- The yearly consumed biomass $\dot{m}$ within the system must not be higher as the sum of the limited biomass potential from residues ϕ^{res} and the limited land use potential Λ^{Land} multiplied with the corresponding yield Y of the energy crop (2.3).

- The yearly maximal allowed amount of GHG emissions ε^{max}, representing the federal climate targets in Germany, must be greater or equal to the sum of the technology-based ε^{rel} and feedstock-based ε^{feed} emissions (2.4).
- The relationship between the produced heat and the utilised feedstock product is given in equation (2.5) and determined by the conversion efficiency η of each technology.
- Equation (2.6) to (2.9) explain the relationship between the number of heating systems installed (n^{cap}) at time point t, the number of heating systems newly invested in (n^{ext}) and the number of heating systems decommissioned (n^{dec}).
- The status quo of all installed heating systems in 2015 serves as a starting point ($n^{initial}$). This portfolio is linearly decommissioned over the corresponding lifetime of each technology ($n^{initialdec}$).
- Heating systems newly installed in the model (n^{ext}) are decommissioned after they have reached their lifetime, defined by the variable n^{extdec}.
- Premature decommissioning of heating systems is only allowed for fossil technologies and limited to 1%/a.
- As a restriction for energy crops, every crop type may maximally double its land use per year.

Linkage to the power sector The heat sector will most likely be strongly linked to the power sector, especially when CHP and power to heat options will be used to a larger extent. To generate conclusive results for the heat sector in the modeling, a linkage to the power sector is inevitable. In order to achieve this linkage, a structural framework is set up. Tab. 2.1 shows how power demand and production is priced and how emissions are allocated in the model. This framework applies specifically in terms of power consumed for heating and power use of CHP / PV technologies.

Table 2.1: Model linkage of the heat sector to the power sector in terms of power consumed for heating and power use of CHP / PV technologies. The emissions from grid-based electricity are allocated to the heat sector in accordance to a scenario defined power mix specific emission factor.

Power	Price	Credit	Heat sector emissions
external demand	Final consumer price	0	Emissions from grid power mix
internally used for heating	0	0	Emissions from techn. system
internally used for non heating	0	Final consumer price	0
fed into the grid	0	Stock market price	0

Additionally, certain input parameters, such as the electricity price, the electricity-mix specific emission factor and the CO_2 certificate price, which are highly influential for the market development of the heat sector, do also rely strongly on the development of the power sector. These parameters are defined in a consistent scenario.

The several components of the power price (e.g. stock market price, taxes and levies) are treated separately in the model. The future stock market power price development is set according to national energy scenario results. In paper 1 and 2 the future price development of taxes and levies is directly derived from this development by calculating a proportional increase or decrease using a factor. In paper 3 this method is improved by setting the future development of the taxes and levies according to projected trends for each component [19, 18, 4]. However, treating the components separately leads to different power prices in the heat sub-sectors (private household, trade/ commerce and the industry), despite applying the same projection for the stock market power price. The different price categories are calculated consumption-based according to the monitoring report of the federal network agency of the year 2015 [2].

Consumer choice The integration of consumer choice requires empirical data on consumer behavior for adopting heating systems and a method to integrate this data into the model. A literature review identified empirical data on consumer preferences for adopting residential heating systems based on surveys. Additionally, methodological approaches were identified applying consumer segmentation and indirect costs into ESOMs to represent consumer heterogeneity. In this thesis, the integration of consumer choice is based on the study of Michelsen and Madlener [35], performing a cluster analysis and an analysis predicting cluster membership (cluster segmentation) on their collected survey data. This cluster segmentation is the basis for splitting the relevant heat sub-sectors into consumer segments. The heat demand of all five single-family sub-sectors, responsible for $\sim 23\%$ of the German heat demand, were further segmented into three consumer segments (C1..C3) each, representing the identified clusters from Michelsen and Madlener [35]. A schematic of how the consumer segmentation and the application of indirect costs is realized in the model is shown in Fig. 2.2. This figure and the following detailed description of the method is quoted from paper 3.

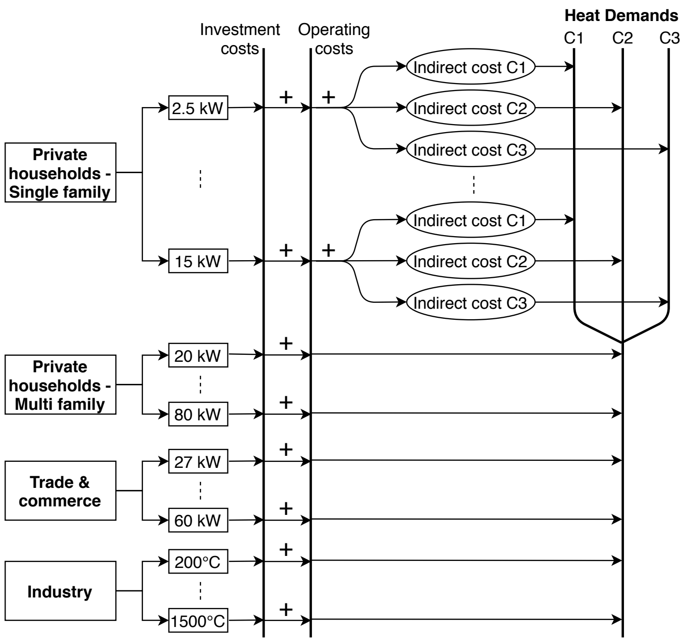

Figure 2.2: Schematic of applying indirect costs in the different consumer segments C1..C3 within the optimization model [23]. The sub-sectors are defined by the size of the heating system, e.g. 2.5 kW.

The adoption of a heating system is mostly driven by financial motives, but also by non-financial motives (mainly comfort and environmental reasons). The financial aspects are comprehensively represented in the optimization model (investment, fixed and variable costs). The non-financial motives are represented via indirect technology costs. In each consumer segment, different indirect costs are applied, following established approaches in literature [31, 32, 46, 8, 39]. In this case, the indirect costs are derived from the membership prediction of different heating systems to one of the three clusters, presented as average marginal effect (M.E.). This marginal effect is translated into indirect costs derived from an economic textbook approach: according to economic theory, market shares of two technologies sh_1 and sh_2 should be inversely related to their relative cost c_1/c_2 [53], with the parameter g indicating the extent to which cost differentials between competing technologies affect their market shares.

$$\frac{sh_1}{sh_2} = \left(\frac{c_2}{c_1}\right)^g \; with \; g > 0 \tag{2.10}$$

As a conclusion derived from this causality, an increased probability of technology market shares (probability of cluster membership, see Michelsen and Madlener [35]) is translated into a decrease in costs and vice-versa. Since market shares in the optimization model are purely based on costs, represented in the objective function, we here translate the probability of cluster membership directly into an indirect cost factor icf for each applicable technology system within the consumer segments. In an ideal case, the indirect costs factor would be calibrated with the parameter g, which was not possible here. The indirect cost factor is implemented into the objective function by adding the inverted indirect technology costs proportional to the investment and variable costs of each technology, see the bold part of equation (2.11). With this method, also negative indirect costs can apply, representing a willingness to pay.

Objective function

$$\begin{aligned} min \sum_{t,i,s,b} mc_{t,i,s,b} \cdot \pi_{t,i,s,b} + \sum_{t,i,j,s} ic_{t,i,j,s} \cdot n^{cap}_{t,i,j,s} \cdot \frac{q(1+q)^{\hat{t}_j}}{(1+q)^{\hat{t}_j} - 1} \\ + \sum_{\mathbf{t,i,s,c}} -\mathbf{icf_{i,c}} \cdot \mathbf{mc_{t,i,s}} \cdot \pi_{\mathbf{t,i,s,c}} + \sum_{\mathbf{t,i,j,s,c}} -\mathbf{icf_{i,c}} \cdot \mathbf{ic_{t,i,s}} \cdot \mathbf{n^{cap}_{t,i,j,s,c}} \cdot \frac{\mathbf{q(1+q)^{\hat{t}_j}}}{\mathbf{(1+q)^{\hat{t}_j} - 1}} \end{aligned} \tag{2.11}$$

subject to

$$\delta_{t,s,c} = \sum_i \pi_{t,i,s,c}, \forall (t,i,s=1..5,c) \in (T,I,S,C) \tag{2.12}$$

$$\sum_c \pi_{t,i,s,c} = \pi_{t,i,s}, \forall (t,i,s=1..5,c) \in (T,I,S,C) \tag{2.13}$$

$$n^{cap}_{t,i,s,c} \cdot \kappa_{t,s} = \pi_{t,i,s,c}, \forall (t,i,s=1..5,c) \in (T,I,S,C) \tag{2.14}$$

$$\sum_c n^{cap}_{t,i,s,c} = n^{cap}_{t,i,s}, \forall (t,i,s=1..5,c) \in (T,I,S,C) \tag{2.15}$$

For the incorporation of consumer choice, four additional restrictions were added to the original model formulation:

- The heat demand δ in each cluster c of the five sub-sectors s needs to be fulfilled by the sum of the produced heat π of all technologies i within one cluster (2.12).
- The sum of heat produced over all clusters needs to equal the heat production within its sub-sector (2.13).
- The sum of heating systems installed n^{cap} multiplied with their individual capacity κ equals the yearly heat production of each technology within its cluster (2.14).
- Equation (2.15) is equivalent to equation (2.13) in relation to n^{cap}.

2.3 Uncertainty assessment

Beside various scenario analysis, the variance-based sensitivity analysis of Sobol' was applied to systematically assess which uncertain input factors are responsible for the uncertainty in the model output. Model parameters with a possible uncertainty in their future development were selected to be varied in the sensitivity analysis. The choice and the uncertainty range of the parameters were obtained through existing studies or expert elicitation. A schematic of how the Sobol' method is applied to the model can be found in Fig. 2.1 and the associated following description is quoted from Paper 2.

Sobol' sensitivity analysis studies the scalar model output $f(p)$ if the model parameters are varied within their uncertainty range. After N model runs with different parameter sets, the variance $V = V(f(p))$ of the scalar output $f(p)$ is split into component variances V_i from individual parameters or parameter interactions. The first order model sensitivity to each parameter p_i is quantified with the first-order Sobol' index S_i, also known as the main effect. The total-order Sobol' index S_{Ti} represents the total effect of parameter p_i and its interaction with all other parameters. A more detailed description of the Sobol' method and how to apply it on models can be found in Saltelli [42], Saltelli et al. [43].

In this thesis, an algorithm was chosen to calculate the Sobol' main effect and total effect with $N(k+2)$ model evaluations [42]. The method used to calculate the Sobol indices requires two independent matrices A and B both containing N sets of k parameters. In this case, k is the number of parameters and N is the sample size used for the random value estimate for parameters being varied. For the random value estimate, Cuntz et al. [11] recommends the use of e.g. stratified sampling such as latin hypercube sampling, which was applied in this study with a sample size of $N = 1000$. The latin hypercube sampling technique evenly samples from the probability distributions [33]. The additionally required matrix $A_B^{(i)}$ has all columns of $A(B)$ except the i^{th} column, which comes from B(A). The exact formulation of the indices S_i and S_{Ti} are chosen from Table 2 (b), (f) of Saltelli et al. [43], which are described as being *best practice*.

$$S_i = \frac{1}{V}\left[\frac{1}{N}\sum_{j=1}^{N} f(B)_j \left(f(A_B^{(i)})_j - f(A)_j\right)\right] \tag{2.16}$$

$$S_{Ti} = \frac{1}{V}\left[\frac{1}{2N}\sum_{j=1}^{N} \left(f(A_B^{(i)})_j - f(A)_j\right)^2\right] \tag{2.17}$$

Both Sobol' indices range from 0 to 1. $S_{Ti} \geq S_i \geq 0$. If $S_{Ti} = S_i = 0$ the parameter is non-influential. If $S_{Ti} = S_i$ there is no interaction of the i^{th} parameter with other parameters.

The scalar model output $f(p)$, on which the Sobol' indices are applied to in this study, is defined by calculating the share of the consumed biomass $\dot{m}$ of each biomass product b in relation to the sum of all biomass products used for heating. In each case, the biomass was summed over the complete time span *t=2015-2050*.

$$f(p = 1..k) = \frac{\sum_{t=2015}^{2050} \dot{m}_{t,b}}{\sum_{t=2015}^{2050} \sum_{b=1}^{20} \dot{m}_{t,b}}$$

The optimization model is evaluated $N(k+2) = 34000$ times. To overcome the computational burden, the calculations were executed on a model server grid.

A visual depiction of how the Sobol' method is applied to the ESOM can be found in Fig. 2.1. Based on the significance of the calculated Sobol' indices, scatter plots and min/ max plots are generated to further analyze how the significantly influencing input parameters impact the model outcome $f(p)$. Based on this analysis, a solution space is quantified for the future cost-optimal use of biomass in the German heat sector under uncertain developments.

Chapter 3

Results and discussion

The future role of biomass within the German heat transition is investigated in this thesis using an ESOM to determine an efficient, cost-optimal use of biomass in different heat subsectors from a systems perspective. A focus is set on a detailed representation of the various technological bioenergy options and possible renewable hybrid heat provision solutions. The heterogeneity of the heat sector is especially considered in terms of the complexity of the demand structure and behavioral characteristics of the manifold consumers. A further focus is set on the investigation of future uncertainties of e.g. technology innovation, resource availability, future feedstock price developments and socioeconomic dynamics. For this purpose, different methodological approaches were combined to integrate consumer choice in the model and to conduct a comprehensive uncertainty assessment.

The results of the modeling are in line with the expectation that major heat supply shares within the heat transition will be provided by heat pumps. The future role of bioenergy in the heat sector has been reevaluated with a high level of detail. Besides the expected use of biomass in the provision of industrial heat, further robust applications and insights for bioenergy in the German heat sector have been identified under the consideration of a variety of uncertainties. With the outlined results a wider basis for the design of an economically and environmentally friendly heat sector in Germany is provided.

The results, discussion and conlusions of the preformed investigations are described in detail in the attached papers. In this section, the main findings from the papers are related to each other and the research questions. A discussion on policy implications is carried out.

3.1 Scenario results

In paper 1, a 95% GHG reduction scenario is investigated with two cases of available biomass potential. The results show that the defined climate target can be achieved until 2050 and that solid biomass has in both cases a competitive role. As expected, the major market shares shift from fossil based technologies to power based heat pumps until 2050. The available biomass potential is found to be most cost efficiently used, until 2040, in the private household sector in decentralized hybrid CHP combustion applications using residual wood as feedstock. The use of biomass in the private household sector in the near future is in line with other studies [40, 27], in which also a high increase in future power prices are assumed. The use of this biomass in hybrid CHP technologies is on the other hand a unique finding. With increasing power prices, the internal power generation in these hybrid systems leads to a competitive advantage. The most cost efficient hybrid system is found in a CHP (torrefied-) pellet combustion plant in combination with a heat pump and a PV-system. Hybrid systems using log wood are less competitive as their market shares decrease with decreasing available biomass potential.

From 2040 onwards, with an increasing GHG reduction target, the use of wood chips from residues and energy crops in high temperature industry applications is found to be the most cost efficient way to reduce the heat based emissions by 95% in the defined scenarios. The use of biomass in high temperature industry applications in ambitious GHG reduction scenarios is in line with several long term energy scenarios [40, 45, 17]. The reason for the competitiveness of biomass in this sector is the lack of competitive, renewable alternatives. Beside bioenergy the electric arc furnace is a renewable option or the use of green hydrogen, which was not modeled in this thesis. Within the scenarios, prime costs of the electric arc are increasing strongly in 2050 compared to biomass heating or heat pumps in the private household sector. The heat pump is more efficient and more cost effective than the electric arcs. Additionally, the use of electric arcs requires significantly more renewable electricity capacity than the use of heat pumps, which also make use of ambient heat. Consequently, in this case, biomass is most efficiently used in high temperature industry applications, avoiding the use of electric arcs from a systems perspective.

Available arable land in the model is cultivated endogenously with the type of energy crops best suited to the optimal resource usage with regard to the objective function. In both cases, energy crops for biogas production, representing the status quo in the starting year, are replaced by Miscanthus, which is almost completely used in the form of wood chips in high temperature industry applications. High yields and low production costs of Miscanthus lead to a monopoly position among energy crops in the modeling. However, in reality, several major barriers, arising to a large extent from the long term commitment, lead to the situation that Miscanthus plays only a minor role in agriculture today.

In the trade and commerce sector, as well as in district heating, biomass is not found to be a future, competitive option in the scenarios. For district heating, biogas plants exist today as a result of federal subsidies in the last decades. Without this support, biogas shares are dropping rapidly, which is also found in other studies [27, 40, 44, 49].

3.2 Uncertainty assessment

Scenario analysis, as performed in paper 1, are one of the simplest ways to address uncertainty [12] and can only assess a limited range of outcomes. To address this shortcoming, a comprehensive uncertainty assessment is performed in paper 2. The optimization model is combined with the global sensitivity analysis of Sobol' to investigate the influence of the future uncertainty in 32 input parameters (incl. e.g. technology innovation, resource availability, future feedstock price developments) on the future bioenergy market shares.

Based on the results of the sensitivity analysis, it is found that in 99,6% of all 34000 model evaluations the climate targets could be fulfilled and therefore we conclude that the heat transition in Germany is possible from a techno-economic view, despite all the future uncertainties. Second, in all cases, almost the complete available biomass potential, pre-allocated for heating, is used in the model, resulting in total bioenergy net market shares of 10 - 25%. Furthermore, 16 out of 20 biomass products are found to have unrelevant market shares. Therefore the following discussion of the results is concentrated on the remaining four: Wood chips and wood pellets from residues, log wood and Miscanthus chips.

Based on the calculated Sobol' index and the resulting scatter and min/max plots, three parameters could be identified, which are significantly influential on the future market shares of bioenergy. Moreover, two parameters have amplifying effects, but do not influence the technology choice significantly.

- **Power and gas price**: major impact on the bioenergy technology competitiveness
- **Climate target**: changes the technological competitiveness from 2040 onwards; with higher climate targets the share of wood chips is increased
- Biomass potential/ biomass pre-allocation: amplifies/ weakens the technology market shares, but does not influence the choice of the technology
- High discount rate: amplifies the market share in favor of wood chip technologies and against log wood gasification systems, but does not change the technology choice

Based on these findings the most robust technology concepts are identified and a solution space shaped by the significant influential parameters is quantified. The most robust use of biomass is found to be in the form of wood chips from residues and Miscanthus in (high temperature) industry applications. A combined minimum biomass use of 25% over the entire modeling period over all calculated sensitivities is a strong indication of robustness. Additionally, the solution space shows major market shares for wood chips, especially towards 2050, see Fig. 3.1.

In the scenario analysis in paper 1, hybrid CHP systems are found to be a competitive option until 2040. The uncertainty assessment in paper 2 reveals that these technological concepts are only a competitive option, if power prices increase strongly. Additionally, in paper 1 and 2 the calculation of the future power price supplements are based on a factorial projection and not on literature projections as applied in paper 3, see Sec. 2.2. Consequently, a wider range of possible future power end consumer price developments, in regards to the upper limit, is investigated in this study. This indicates that a strong increase in power prices is necessary for a competitive business case of hybrid CHP pellet systems. However, increasing power prices are likely to lead to an competitive advantage of natural gas technologies compared to heat pumps, which are power based renewable technologies. According to the findings in this thesis and national energy scenarios, as e.g. [40, 44], heat pumps have to be the major renewable substitute for fossil heat technologies to fulfill the GHG reduction targets in the heat sector. Consequently, even with increasing CO_2 prices, a high level of power prices might slow down or even prevent a successful heat transition. In this case, competitive hybrid CHP pellet systems can only contribute to a minor share of the German heat transition as the biomass potential is limited.

This example shows the importance of a comprehensive sensitivity assessment, investigating a wide range of solutions, as the importance of hybrid CHP pellet systems would have been overrated if only a scenario analysis would have been performed. Another example is the finding of a competitive log wood concept through the outlined uncertainty assessment, which was not identified to be competitive in the scenario analysis. If gas prices increase and power prices remain on the current level, a log wood gasification boiler combined with a solar thermal system gains major market shares in the medium term. However, in the long term, market shares decrease and the use of the available biomass shifts to high temperature industry applications, see Fig. 3.1.

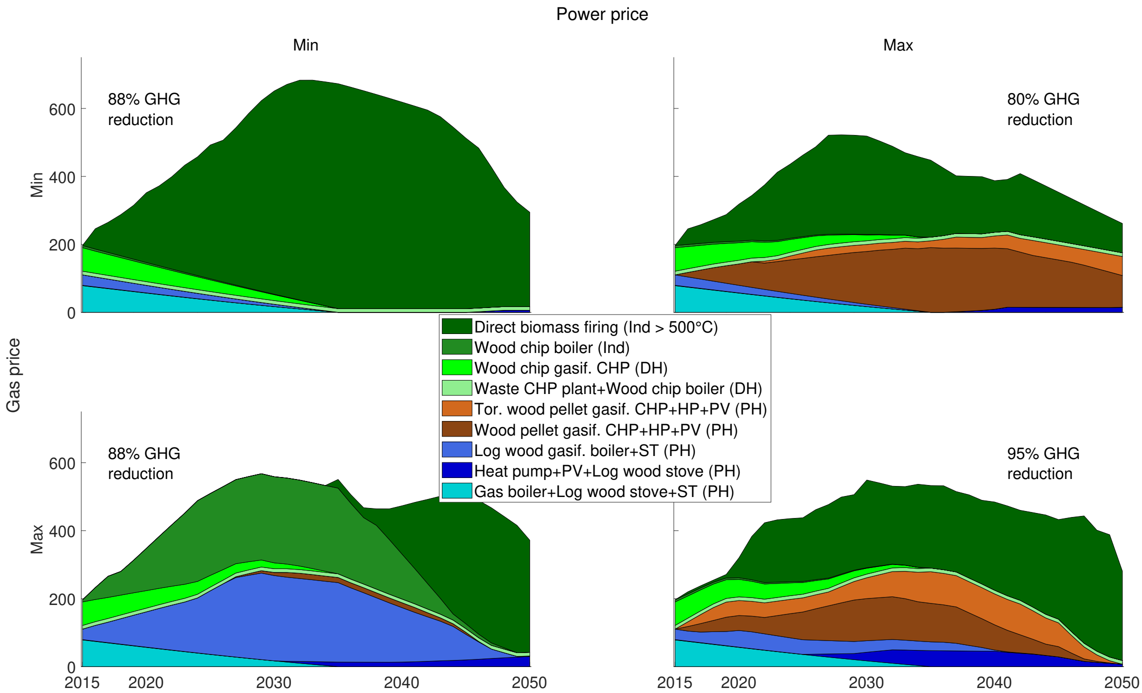

Figure 3.1: Calculated solution space for the choice of bioenergy technologies, considering the defined uncertainties in paper 2. Displayed are the net energy market shares of the relevant bioenergy technologies in PJ. Within the figure only the relevant bioenergy technology concepts are shown, leaving out fossil references, alternative renewable technologies and unrelevant bioenergy concepts. For hybrid systems, only the solid biomass net energy shares of the concepts are displayed in order to have a depiction of the biomass utilization. Ind = Industry; DH = District Heating; PH = Private Households; CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST = Solar Thermal

Several finding from the scenario analysis are confirmed with the sensitivity assessment: From the available energy crops in the model, Miscanthus remains in all cases the most competitive option, despite the large variation in which the expected yield was varied (±33%). Additionally, in district heating and the trade and commerce sector no competitive applications for bioenergy could be identified under consideration of the investigated uncertainties.

The novel approach of combining an ESOM with the global sensitivity analysis of Sobol' investigates a wide range of uncertainty and possible outcomes and therefore improves the robustness of model results. However, not all possible future uncertainties related to the future development of the heat sector were considered in paper 2, as e.g. the influence of consumer behavior.

3.3 Consumer choice

In paper 3 of this thesis, consumer choice was integrated into the model to determine its impact on the future use of bioenergy in two scenarios and in a sensitivity analysis analog to paper 2. In this investigation, a GHG reduction target is not applied. The model is used to project the future market development under the assumption of economically rational behavior of all actors, except for the behavioral aspects integrated into the model. This includes that all actors have perfect foresight, and future price and demand developments are known by the consumers. A business as usual (BAU) and an ambitious measures scenario (AMS) are analyzed, both calculated with and without the implementation of consumer choice. In the BAU scenario energy prices are kept at a constant level and no CO_2 pricing is in place. The AMS scenario is characterized by an ambitious CO_2 pricing, constantly increasing up to 200 €/tCO_2eq in 2050.

The results show that if consumer choice is not applied, a typical picture for optimization results develops: only a few technologies gain the major market shares compared to the wider portfolio of the starting year. The use of biomass shifts almost completely to high temperature industry applications, confirming the findings of paper 1 and 2. The integration of consumer choice leads to a higher diversity in technology market shares in both scenarios. In the BAU scenario, the market shares of the starting portfolio remain more or less constant over time and the model delivers more plausible results. Especially in the private household sector, log wood and pellet technologies remain competitive, in addition to the use of biomass in industry applications.

For the ambitious measures scenario a similar picture for bioenergy develops. Without applying consumer choice, the available biomass is exclusively distributed into industry applications. On the other hand, when consumer choice is activated in the model, log wood technologies remain competitive. The future competitiveness of log wood technologies under consideration of consumer choice is one of the main findings in this study, which is also confirmed by the sensitivity analysis applied in paper 3. This finding complements the findings in paper 1 and 2, in which consumer choice was not considered. In paper 1 and 2 log wood technologies were identified not to be robust competitive future options and are only competitive under certain conditions.

A detailed look into the consumer segments of both scenarios reveals that the technology types with the largest market shares are those which, according to the findings of Michelsen and Madlener [35], are preferred by the consumers of the different segments C1..C3. The only exception is found in sub-sectors representing high insulation standards. In these sub-sectors the economic advantages of heat pumps or gas technologies exceed the non-economic factors.

3.4 Limitations

The analyses in this thesis are designed as simple as possible and as complex and detailed as necessary to address the defined research questions and therefore high quality results could be generated. However, every analysis has its limits. For instance, the heat sector does not need to be modeled in a high temporal resolution as heat prices do not vary on a hourly basis as in the power sector. This opens up the opportunity to apply a comprehensive uncertainty assessment, due to the short model run time. However, increasing the annual resolution to an at least monthly one seems worthwhile to investigate, since the heat demand, PV yield, etc. varies seasonally. Additionally, the effect of a cross-sectoral analysis on the optimal biomass allocation within the heat sector can be discussed and would require a higher temporal resolution. However, it was intended to cover this effect of a cross-sectoral analysis with the uncertainty analysis by varying the available biomass potential and the relevant power sector parameters.

The complexity and heterogeneity of the heat sector is represented in a high level of detail, especially for the private household sector. For the industry and district heating sector a similar detailed approach was not possible, due to the limited available data basis. On the other hand, it was possible to analyse the private houshold sector not only from a technical view, but also consider consumer behavior. However, limitations exist with regard to the data basis and the methodological basis when implementing consumer choice in the analysis. Especially, more recent and detailed empirical data on homeowners' investment decisions are desirable. Additionally, and perhaps most challenging, is that behavior changes over the course of time and is difficult to project [12, 6]. However, the results show how important it is to extend the analysis beyond techno-economics. Besides consumer behavior, e.g. the consideration of particulate matter emissions seems worthwhile to investigate.

Further limitations are identified in the projection of future biomass feedstock prices. Today, dependencies exist e.g. between the pellet and natural gas prices. The development of these dependencies towards a climate neutral energy system in 2050 is difficult to project.

3.5 Summary

A summary of the overarching paper findings on the cost-optimal use of biomass within the German heat transition is presented in Tab. 3.1.

Table 3.1: A sketch of the prioritization of biomass allocation for heating in competitive bioenergy concepts.

	Prioritization of biomass allocation
Wood chips (residues or Miscanthus)	Most robust option in high temperature industry applications under all investigated uncertainties.
Log wood	Additional future demand may persist in one and two family houses under consideration of consumer preferences (low to medium insulation standard).
Hybrid CHP pellet concepts	Competitive option in buildings given strongly increasing power prices, which are counterproductive for the heat transition.

The findings are based on the results of a detailed modeling of the German heat sector using a linear optimization approach. The model was applied in several scenario analysis. Additionally, a comprehensive sensitivity assessment was conducted under consideration of consumer behavior.

Chapter 4

Conclusions

The objective of this thesis is to provide a wider basis for the transition process in the diverse heat sector in Germany towards an economically and environmentally friendly system. For this purpose, a model was set up to investigate the future cost-optimal use of bioenergy within the German heat transition from a systems perspective. The model delivers plausible results, which are in line with national energy scenario analyses. Additionally, the thesis delivers detailed insights on the cost optimal future use of bioenergy within the German heat transition.

First of all, the investigations show that the heat transition in Germany is possible from a techno-economic view, as in almost all model evaluations the climate targets could be fulfilled under the uncertainties investigated. Additionally, it is found that solid biomass in the form of either wood chips, pellets, log wood or Miscanthus chips is in all investigated cases a cost competitive renewable heat provision option to fulfill the defined climate targets. The most robust bioenergy option is found in the form of wood chips from residues or Miscanthus in high temperature industry applications. Due to the fact that in this sub-sector the alternative renewable technologies are rare and e.g. renewable power can be more efficiently used in heat applications in the private household, trade and commerce sector, biomass is, from a systems perspective, within the heat sector most efficiently allocated in high temperature industry applications. This finding applies especially to cases with a high GHG reduction target, which needs to be established by defining a GHG reduction roadmap. Committing the industry to decarbonize its processes will lead to the efficient use of biomass in high temperature industry applications.

Log wood technologies in the private household sector are found to be an additional competitive option, especially when the heterogeneity in consumers and behavioral factors are considered. Certain consumer groups in the private household sector are willing to pay more for log wood and also pellet technologies and therefore a future demand for these bioenergy technologies may persist in this sector. However, the analyses show that in houses with high insulation standards, economic factors exceed behavior factors.

Hybrid CHP pellet systems are found to be a competitive option for the next decades under the assumption of strongly increasing power prices. However, increasing power prices are likely to lead to a competitive advantage of natural gas technologies compared to heat pumps, which are expected to be fundamental for the heat transition. Consequently, increasing power prices are likely to decelerate the heat transition. Efforts should therefore be made to maintain the power price level at the current level, under which hybrid CHP pellet systems are not found to be a competitive option.

Political implications: In this thesis, methods have been used that identify parameters, which impact the model outcome significantly and how they do so. Consequently, when designing policies, these factors should be in the focus. The uncertainty assessments show that the future development of the power and gas price as well as the consideration of consumer choice in the model have a significant influence on the future competitiveness of bioenergy. As mentioned before, power prices should remain at the current level. End consumer gas prices need to increase, by e.g. applying a CO_2 emission allowance price at the necessary level. This level depends on the price development of fossil feedstocks, renewable feedstocks and the power prices. Therefore, a flexible adjustment of a CO_2 emission allowance price seems necessary. On the other hand, heat consumers need security in planning to invest in renewable technologies. Furthermore, the heterogeneity of consumers in the private household sector and their potential log wood demand, which might persist in the future, should at least be discussed when designing policies. Finally, from the available energy crops, Miscanthus is found in all cases to be the most competitive option. Despite several major barriers, arising to a large extent from the long term commitment of growing perennial crops, this finding should be discussed when designing policies. In summary, if politicians create a technology open framework for the German heat transition, they can expect a demand for bioenergy in the long term. However, the use of sustainable biomass should always be in the focus, as it has also been the basis for all investigations laid out in this theses. Regardless of the application segment for material or energetic usage, a sustainable, limited biomass supply is necessary, which requires an overarching political framework.

With the outlined thesis, novel methodological approaches are introduced. They are contributing to both the uncertainty assessment in energy system analysis and the integration of consumer heterogeneity and behavioral factors in ESOMs. The methodological progress in assessing uncertainty leads to policy insights with a high level of confidence and can serve as a case study or guideline for other researchers. The introduced method can also be applied to other regions.

4.1 Future research

Based on the limitations, results and conclusions in this thesis the following future research gaps are identified to improve the basis for the design of an economically and environmentally friendly heat sector. It was found that biomass will play a particularly competitive, future role in the industry. A more detailed look into this sector regarding a further differentiation of the different business sectors, temperature levels and load profiles is highly recommended by the authors to identify in which concrete applications the limited potential of biomass is cost optimally allocated. In addition, hydrogen technologies should be integrated into this analysis, as hydrogen is currently discussed in many industrial applications as a future green solution. The biggest obstacle for realizing this analysis is the current limited available data basis. This issue is comprehensively discussed in Lenz et al. [30].

Another research topic identified is the analysis of a necessary CO_2 price level, appropriate funding instruments or policy steering instruments for realizing a heat transition in Germany. The interaction of the CO_2 price and the future, uncertain development of energy prices, especially the gas, power and biomass price developments, is expected to have a great influence on the achievement of the climate targets. This effect can be well investigated with the uncertainty assessment introduced in this thesis. When different instruments are being implemented in the model, societal influences need to be integrated as well. In this thesis, it is found that the methodological and the data basis for integrating consumer choice into the model is limited. For future research, more recent and detailed empirical data and methodological progress, as e.g. a model calibration would be desirable.

Further research potentials were identified in data availability and methodological improvements to generate insights with a higher level of confidence. For instance, the pricing of biomass feedstocks, especially for the future, is difficult to specify. In reality, certain biomass prices vary regionally, which is different to e.g. power and gas prices. Today wood pellet prices are somehow connected to the gas price. How does this develop in a world based on renewable energies? Is there a correlation or dependence between the prices of biomass residues and biomass from energy crops? A consistent method representing the future biomass price developments would increase the confidence in model results.

Finally, it seems worthwhile to investigate the effect of an increased temporal and spatial resolution. With an increased spatial resolution, the regional availability of biomass could be represented and the possible extension of district heating networks could be investigated. An increased temporal resolution offers the possibility to further investigate the effect of sector coupling, especially with regard to the power sector. Seasonal variations of e.g. the heat demand, solar thermal yield and of renewable power fluctuations could be assessed.

Bibliography

[1] Gesamtausgabe der Energiedaten - Datensammlung des BMWi, . URL https://www.bmwi.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html.

[2] Monitoringbericht 2016, . URL https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2016.pdf;jsessionid=907DA6C77633E11849D9FC3746057EC5?__blob=publicationFile&v=2.

[3] Surveys of the chimney sweep trade (Erhebungen des Schornsteinfegerhandwerks), .

[4] Evaluation of reference studies and scenario analyses on the future development of grid charges for electricity (BMWi-Vorhaben Netzentgelte: Auswertung von Referenzstudien und Szenarioanalysen zur zukünftigen Entwicklung der Netzentgelte für Elektrizität). URL https://www.agora-energiewende.de/fileadmin2/Projekte/2015/EEG-Kosten-bis-2035/Agora_EEG_Kosten_2035_web_05052015.pdf.

[5] Bioenergie, 2020. URL https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/bioenergie.

[6] Silke Borgstedt, Tamina Christ, and Fritz Reusswig. Environmental awareness in germany 2010 (Umweltbewusstsein in Deutschland 2010): Results of a representative population survey (Ergebnisse einer repräsentativen Bevölkerungsumfrage). URL https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4045.pdf.

[7] André Brosowski, Tim Krause, Udo Mantau, Bernd Mahro, Anja Noke, Felix Richter, Thomas Raussen, Roland Bischof, Thomas Hering, Christian Blanke, Paul Müller, and Daniela Thrän. How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany. *Biomass and Bioenergy*, 127:105275, 2019. ISSN 09619534. doi: 10.1016/j.biombioe.2019.105275.

[8] David Bunch, Kalai Ramea, Sonia Yeh, and Christopher Yang. Incorporating Behavioral Effects from Vehicle Choice Models into Bottom-Up Energy Sector Models.

[9] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung: Kurzfassung. URL http://www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_kurzf_bf.pdf.

[10] Bundesministerium für Wirtschaft und Energie. Energy data (Energiedaten): Complete edistion (Gesamtausgabe). URL https://www.bmwi.de/Redaktion/DE/Downloads/Energiedaten/energiedaten-gesamt-pdf-grafiken.pdf?__blob=publicationFile&v=40.

[11] Matthias Cuntz, Juliane Mai, Matthias Zink, Stephan Thober, Rohini Kumar, David Schäfer, Martin Schrön, John Craven, Oldrich Rakovec, Diana Spieler, Vladyslav Prykhodko, Giovanni Dalmasso, Jude Musuuza, Ben Langenberg, Sabine Attinger, and Luis Samaniego. Computationally inexpensive identification of noninformative model parameters by sequential screening. *Water Resources Research*, 51(8):6417–6441, 2015. ISSN 00431397. doi: 10.1002/2015WR016907.

[12] Joseph DeCarolis, Hannah Daly, Paul Dodds, Ilkka Keppo, Francis Li, Will McDowall, Steve Pye, Neil Strachan, Evelina Trutnevyte, Will Usher, Matthew Winning, Sonia Yeh, and Marianne Zeyringer. Formalizing best practice for energy system optimization modelling. *Applied Energy*, 194:184–198, 2017. doi: 10.1016/j.apenergy.2017.03.001.

[13] Diane F. DiClemente and Donald A. Hantula. Applied behavioral economics and consumer choice. *Journal of Economic Psychology*, 24(5):589–602, 2003. ISSN 01674870. doi: 10.1016/S0167-4870(03)00003-5.

[14] FVEE-Themen. Forschung für die Wärmewende: Beiträge zur FVEE-Jahrestagung 2015. 2015. URL http://www.fvee.de/fileadmin/publikationen/Themenhefte/th2015/th2015.pdf.

[15] GAMS Development Corp. GAMS, 2019. URL https://www.gams.com/.

[16] Maurizio Gargiulo and Brian Ó. Gallachóir. Long-term energy models: Principles, characteristics, focus, and limitations. *Wiley Interdisciplinary Reviews: Energy and Environment*, 2(2):158–177, 2013. ISSN 20418396. doi: 10.1002/wene.62.

[17] Philipp Gerbert, Patrick Herhold, Jens Burchardt, Stefan Schönberger, Florian Rechenmacher, Almut Kirchner, Andreas Kemmler, and Marco Wünsch. Klimapfade für Deutschland.

[18] Philipp Götz, Johannes Henkel, and Thorsten Lenck. Relationship between power exchange prices and end customer prices (Zusammenhang von Strombörsenpreisen und Endkundenpreisen): Study commissioned by Agora Energiewende (Studie im Auftrag der Agora Energiewende). URL `https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/netzentgelte-auswertung-von-referenzstudien.pdf?__blob=publicationFile&v=6`.

[19] Markus Haller, Mara Marthe Kleiner, and Verena Graichen. The development of renewable act costs until 2035 (Die Entwicklung der EEG-Kosten bis 2035): How the expansion of renewables works along the long-term goals of the energy transition (Wie der Erneuerbaren-Ausbau entlang der langfristigen Ziele der Energiewende wirkt). URL `https://www.agora-energiewende.de/fileadmin2/Projekte/2015/EEG-Kosten-bis-2035/Agora_EEG_Kosten_2035_web_05052015.pdf`.

[20] Klaus Heuck, Klaus-Dieter Dettmann, and Detlef Schulz. *Elektrische Energieversorgung: Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis*. Vieweg + Teubner, 8 edition, 2010.

[21] Jean-Charles Hourcade, Mark Jaccard, Chris Bataille, and Frederic Ghersi. Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of "The Energy Journal". *The Energy Journal*, (27):1–11, 2006. URL `https://www.jstor.org/stable/23297043`.

[22] Matthias Jordan, Volker Lenz, Markus Millinger, Katja Oehmichen, and Daniela Thrän. Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach. *Energy*, 189:116194, 2019. ISSN 03605442. doi: 10.1016/j.energy.2019.116194.

[23] Matthias Jordan, Charlotte Hopfe, Markus Millinger, Julian Rode, and Daniela Thrän. Incorporating Consumer Choice into an Optimization Model for the German Heat Sector: Effects on the Projected Bioenergy Use. 2020. URL `https://www.preprints.org/manuscript/202007.0098/v1`.

[24] Daniel Kahneman and Amos Tversky. Choices, values, and frames. *American Psychologist*, 39(4): 341–350, 1984. ISSN 0003-066X. doi: 10.1037/0003-066X.39.4.341.

[25] Gernot Klepper and Daniela Thrän. Biomasse im Spannungsfeld zwischen Energie- und Klimapolitik: Potenziale – Technologien – Zielkonflikte.

[26] Matthias Koch, Klaus Hennenberg, Katja Hünecke, Markus Haller, and Tilman Hesse. Role of bioenergy in the electricity and heating market until 2050, taking into account the future building stock (Rolle der Bioenergie im Strom- und Wärmemarkt bis 2050 unter Einbeziehung des zukünftigen Gebäudebestandes), . URL `https://www.energetische-biomassenutzung.de/fileadmin/Steckbriefe/dokumente/03KB114_Bericht_Bio-Strom-W%C3%A4rme.pdf`.

[27] Matthias Koch, Tilman Hesse, Tanja Kenkmann, Veit Bürger, Markus Haller, Christoph Heinemann, Moritz Vogel, Dierk Bauknecht, Franziska Flachsbath, Christian Winger, Damian Wimmer, Lothar Rausch, and Hauke Hermann. Einbindung des Wärme- und Kältesektors in das Strommarktmodell PowerFlex zur Analyse sektorübergreifender Effekte auf Klimaschutzziele und EE-Integration, . URL `https://www.oeko.de/fileadmin/oekodoc/Einbindung-Waerme-Kaeltesektor-Powerflex.pdf`.

[28] Markus Lauer, Uwe Leprich, and Daniela Thrän. Economic assessment of flexible power generation from biogas plants in Germany's future electricity system. *Renewable Energy*, 146:1471–1485, 2020. ISSN 09601481. doi: 10.1016/j.renene.2019.06.163.

[29] Volker Lenz and Matthias Jordan. Technical and economic data of renewable heat supply systems for different heat sub-sectors., 2019. URL `http://dx.doi.org/10.17632/v2c93n28rj.2`.

[30] Volker Lenz, Nora Szarka, Matthias Jordan, and Daniela Thrän. Status and Perspectives of Biomass Use for Industrial Process Heat for Industrialized Countries. *Chemical Engineering & Technology*, 133 (5):57, 2020. ISSN 09307516. doi: 10.1002/ceat.202000077. URL `https://www.fvee.de/fileadmin/publikationen/Themenhefte/th2019/th2019.pdf`.

[31] David McCollum, Volker Krey, Peter Kolp, Yu Nagai, and Keywan Riahi. Transport electrification: A key element for energy system transformation and climate stabilization. *Climatic Change*, 123(3-4): 651–664, 2014. ISSN 0165-0009. doi: 10.1007/s10584-013-0969-z.

[32] David L. McCollum, Charlie Wilson, Hazel Pettifor, Kalai Ramea, Volker Krey, Keywan Riahi, Christoph Bertram, Zhenhong Lin, Oreane Y. Edelenbosch, and Sei Fujisawa. Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, 55:322–342, 2017. ISSN 13619209. doi: 10.1016/j.trd.2016.04.003.

[33] M. D. McKay, R. J. Beckman, and W. J. Conover. Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, 21(2):239–245, 1979. ISSN 0040-1706. doi: 10.1080/00401706.1979.10489755.

[34] Erik Merkel, Russell McKenna, Daniel Fehrenbach, and Wolf Fichtner. A model-based assessment of climate and energy targets for the German residential heat system. *Journal of Cleaner Production*, 142:3151–3173, 2017. ISSN 09596526. doi: 10.1016/j.jclepro.2016.10.153.

[35] Carl Christian Michelsen and Reinhard Madlener. Motivational factors influencing the homeowners' decisions between residential heating systems: An empirical analysis for Germany. *Energy Policy*, 57: 221–233, 2013. ISSN 03014215. doi: 10.1016/j.enpol.2013.01.045.

[36] M. Millinger, J. Ponitka, O. Arendt, and D. Thrän. Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany. *Energy Policy*, 107: 394–402, 2017. ISSN 03014215. doi: 10.1016/j.enpol.2017.05.013.

[37] Markus Millinger. BioENergyOPTimisation model, 2019.

[38] Sylvio Nagel, Tanja Mast, Uwe Holzhammer, and Ludger Eltrop. Die Rolle der Bioenergie im Energie- und Mobilitätssystem in Deutschland - Ergebnisse einer modellgestützten Systemanalyse. In Michael Nelles, editor, *Tagungsband zum 14. Rostocker Bioenergieforum / 19. DIALOG Abfallwirtschaft MV*. Universität, Agrar- und Umweltwissenschaftliche Fakultät Rostock.

[39] Kalai Ramea, David S. Bunch, Christopher Yang, Sonia Yeh, and Joan M. Ogden. Integration of behavioral effects from vehicle choice models into long-term energy systems optimization models. *Energy Economics*, 74:663–676, 2018. ISSN 01409883. doi: 10.1016/j.eneco.2018.06.028.

[40] Julia Repenning, Lukas Emele, Ruth Blanck, Hannes Böttcher, Günter Dehoust, Hannah Förster, Benjamin Greiner, Ralph Harthan, Klaus Hennenberg, Hauke Hermann, Wolfram Jörß, Charlotte Loreck, Sylvia Ludig, Felix Matthes, Margarethe Scheffler, Katja Schumacher, Kirsten Wiegmann, Carina Zell-Ziegler, Sibylle Braungardt, Wolfgang Eichhammer, Rainer Elsland, Tobais Fleiter, Johannes Hartwig, Judit Kockat, Ben Pfluger, Wolfgang Schade, Barbara Schlomann, Frank Sensfuß, and Hans-Joachim Ziesing. Climate protection scenario 2050 (Klimaschutzszenario 2050): 2. Endbericht -Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit. URL `https://www.oeko.de/oekodoc/2451/2015-608-de.pdf`.

[41] Cornelia Rönsch. Development of a method to use the data of the chimney sweep trade for the energy industry reporting (Entwicklung einer Methode zur Verwendung der Daten des Schornsteinfegerhandwerks für die energiewirtschaftliche Berichterstattung): PhD thesis (Dissertationsschrift).

[42] Andrea Saltelli. Making best use of model evaluations to compute sensitivity indices. *Computer Physics Communications*, 145(2):280–297, 2002. ISSN 00104655. doi: 10.1016/S0010-4655(02)00280-1.

[43] Andrea Saltelli, Paola Annoni, Ivano Azzini, Francesca Campolongo, Marco Ratto, and Stefano Tarantola. Variance based sensitivity analysis of model output. Design and estimator for the total sensitivity index. *Computer Physics Communications*, 181(2):259–270, 2010. ISSN 00104655. doi: 10.1016/j.cpc.2009.09.018.

[44] Michael Schlesinger, Dietmar Lindenberger, and Christian Lutz. Entwicklung der Energiemärkte - Energiereferenzprognose: Projekt Nr. 57/12 Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie. URL `https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht.pdf?__blob=publicationFile&v=7`.

[45] Nora Szarka, Marcus Eichhorn, Ronny Kittler, Alberto Bezama, and Daniela Thrän. Interpreting long-term energy scenarios and the role of bioenergy in Germany. *Renewable and Sustainable Energy Reviews*, 68:1222–1233, 2017. ISSN 13640321. doi: 10.1016/j.rser.2016.02.016.

[46] Jacopo Tattini, Kalai Ramea, Maurizio Gargiulo, Christopher Yang, Eamonn Mulholland, Sonia Yeh, and Kenneth Karlsson. Improving the representation of modal choice into bottom-up optimization energy system models – The MoCho-TIMES model. *Applied Energy*, 212:265–282, 2018. doi: 10.1016/j.apenergy.2017.12.050.

[47] The MathWorks Inc. MATLAB, 2019. URL `https://de.mathworks.com/products/matlab.html`.

[48] Daniela Thrän, editor. *Smart Bioenergy*. Springer International Publishing, Cham, 2015. ISBN 978-3-319-16192-1. doi: 10.1007/978-3-319-16193-8.

[49] Daniela Thrän, Oliver Arendt, Jens Ponitka, Julian Braun, Markus Millinger, Verena Wolf, Martin Banse, Rüdiger Schaldach, Jan Schüngel, Sven Gärtner, Nils Rettenmaier, Katja Hünecke, Klaus Hennenberg, Bernhard Wern, Frank Baur, Uwe Fritsche, and Hans-Werner Gress. Meilensteine 2030: Elemente und Meilensteine für die Entwicklung einer tragfähigen und nachhaltigen Bioenergiestrategie.

[50] Umweltbundesamt. Renewable energies in germany (Erneuerbare Energien in Deutschland): Data on development in 2019 (Daten zur Entwicklung im Jahr 2019). URL `https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-04-03_hgp-ee-in-zahlen_bf.pdf`.

[51] Umweltbundesamt. Erneuerbare Energien in Zahlen, 2018. URL `https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#statusquo`.

[52] Xiufeng Yue, Steve Pye, Joseph DeCarolis, Francis G.N. Li, Fionn Rogan, and Brian Ó. Gallachóir. A review of approaches to uncertainty assessment in energy system optimization models. *Energy Strategy Reviews*, 21:204–217, 2018. ISSN 2211467X. doi: 10.1016/j.esr.2018.06.003.

[53] Peter Zweifel, Aaron Praktiknjo, and Georg Erdmann. *Energy Economics*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2017. ISBN 978-3-662-53020-7. doi: 10.1007/978-3-662-53022-1.

Contribution to Appended Papers

The authors' contribution to the work reported in the appended papers were as follows:

I Jordan, M., Lenz, V., Millinger, M., Oehmichen, K. and Thrän, D. (2019) *Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach.* Energy. 189, art. 116194.

Jordan, Thrän, Lenz and Millinger developed the idea. Jordan developed the model, defined the scenarios and the linkage to the power sector, carried out all the modelling and calculations and wrote the major part of the paper. Lenz provided the technical and economic data on the technology concepts, defined the sub-sectors and wrote section *2.2. Heat sub-sectors* and *2.3. Technology concepts* of the paper. Millinger provided data and the method on the future biomass feedstock price development. Oehmichen calculated the emission factors of the technology concepts and feedstocks. Millinger and Thrän provided expert guidance and feedback on the model results and manuscript.

II Jordan, M., Millinger, M. and Thrän, D. (2020) *Robust bioenergy technologies for the German heat transition: A novel approach combining optimization modeling with Sobol' sensitivity analysis.* Applied Energy. 262, art. 114534.

Jordan had the idea, developed the methodological approach, carried out all the modelling and calculations and wrote the paper. Millinger and Thrän provided expert guidance and feedback on the model results and the manuscript.

III Jordan, M., Hopfe, C., Millinger, M., Rode, J. and Thrän, D. (2021) *Incorporating consumer choice into an optimization model for the German heat sector: Effects on projected bioenergy use.* Journal of Cleaner Production. 295 , art. 126319.

Jordan, Millinger and Thrän had the idea. Jordan developed the methodological approach, carried out all the modelling and calculations and wrote the major part of the paper. Hopfe carried out the literature review on empirical data of consumer behavior and wrote the corresponding sub-section of the paper. Millinger provided expert guidance on the modeling. Rode built the categorization of influencing factors for consumers' heating system choices and provided expert guidance on all behavior related topics. Millinger, Rode, Thrän and Hopfe provided expert guidance and feedback on the manuscript.

IV Jordan, M., Millinger, M. and Thrän, D. (submitted) *Benopt-Heat: An economic optimization model to identify robust bioenergy technologies for the German heat transition.*

Jordan developed the model, its structure and wrote the paper. Millinger provided data and the method on the future biomass feedstock price development and expert guidance on the modeling. Millinger and Thrän provided expert guidance and feedback on the manuscript.

Curriculum Vitae

Matthias Jordan born Martin
Born: June 22, 1982 (Erfurt, Germany)
Nationality: German

Scientific career & Education

since 2017	Scientist at the Helmholtz Centre for Environmental Research (UFZ) in Leipzig
2010-2017	Project Engineer at the Bertrandt AG in Rüsselsheim and Leipzig
2003-2010	Academic Studies of the interdisciplinary course of Mechatronics at the Karlsruhe Institut of Technology (KIT)
2008	Study abroad at the University of Technology Sydney (UTS)
2005	Completion of the “Vordiplom” in the faculty of “Elektrotechnik und Informationstechnik” at the KIT
2002-2003	Civilian Service at the “Institut für Transfusionsmedizin, Klinikum der Albert-Ludwigs-Universität Freiburg i. Br.”
2002	General qualification for university entrance at the “Marie-Curie-Gymnasium” in Kirchzarten

Leipzig, 25 January 2021

Matthias Jordan

Part II

Appended papers

Paper 1

Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach.

Jordan, M., Lenz, V., Millinger, M., Oehmichen, K. and Thrän, D.

Energy (2019), 189, art. 116194.

Energy 189 (2019) 116194

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach

Matthias Jordan [a, *], Volker Lenz [b], Markus Millinger [a], Katja Oehmichen [b], Daniela Thrän [a, b]

[a] Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318, Leipzig, Germany
[b] DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Strasse 116, 04347, Leipzig, Germany

A R T I C L E I N F O

Article history:
Received 17 June 2019
Received in revised form
20 September 2019
Accepted 22 September 2019
Available online 27 September 2019

Keywords:
Heat sector
Bioenergy
Renewable energy
Optimization
Hybrid heat technologies

A B S T R A C T

Meeting the defined greenhouse gas (GHG) reduction targets in Germany is only possible by switching to renewable technologies in the energy sector. A major share of that reduction needs to be covered by the heat sector, which accounts for ~35% of the energy based emissions in Germany. Biomass is the renewable key player in the heterogeneous heat sector today. Its properties such as weather independency, simple storage and flexible utilisation open up a wide field of applications for biomass. However, in a future heat sector fulfilling GHG reduction targets and energy sectors being increasingly connected: which bioenergy technology concepts are competitive options against other renewable heating systems? In this paper, the cost-optimal allocation of the limited German biomass potential is investigated under long-term scenarios using a mathematical optimization approach. The model results show that bioenergy can be a competitive option in the future. Especially the use of biomass from residues can be highly competitive in hybrid combined heat and power (CHP) pellet combustion plants in the private household sector. However, towards 2050, wood based biomass use in high temperature industry applications is found to be the most cost efficient way to reduce heat based emissions by 95% in 2050.

1. Introduction

Global climate change, depleting energy resources and energy security are issues affecting all countries. In Germany ambitious emission reduction and efficiency improvement targets are defined by the government [12]: by 2050, GHG emissions in the energy sector are to be reduced by 80–95% compared to 1990 levels. A major share of that reduction needs to be covered by the heat sector, which accounts for ~ 35% of the energy based emissions [41] and 54% of the final energy demand [10] in Germany today.

The German heat sector is characterized by its heterogeneity due to different demand profiles, applications and infrastructures. Heat consumption takes place in millions of residential buildings (which accounts for 43% of the final heat demand), trade and commerce buildings (17%), as well as in many different fields of the industry (40%) [10], mainly the steel and chemical industries in high temperature applications. Within these sectors, different temporal demands occur, ranging from seasonal to daily fluctuating needs. In addition to this complex demand structure, 8% of heat is not produced at the location of demand, but distributed via district heating grids [10]. To reduce greenhouse gas emissions in the heat sector both the demand and supply sides need to be addressed.

Heat demand in buildings needs to be decreased by increasing the refurbishment rate. Additionally, the heat transition needs different renewable technological solutions that fit this complex market structure, combining renewable power and biomass energy sources.

In 2017, biomass was the largest renewable energy contributor in Germany (54%), particularly in the heat sector where 87% of the renewable energy was covered by biomass. Solid biomass was contributing the highest share of renewable heat with 68% [1]. However, alternative renewable heat options take up more market shares, the resource biomass is limited and a great share of the German yearly usable potential is already exploited [7]. On the other hand, bioenergy has clear advantages compared to other renewable fluctuating energy sources in the heat sector: weather independency, the possibility of simple storage and flexible utilisation, in that biomass in contrast to e.g. power can be stored for

* Corresponding author.
E-mail address: matthias.jordan@ufz.de (M. Jordan).

https://doi.org/10.1016/j.energy.2019.116194
0360-5442/

longer periods of time (in some cases, such as for solid biomass, over seasons) and thus be utilised in times when variable renewables produce little or demand is particularly high (e.g. in winter). These properties open up a wide field of application for biomass within the different sub-sectors of the heat sector. But in which sub-sectors is biomass competitive against other renewable applications, while fulfilling the GHG reduction targets?

Several studies are available on the development of the German energy transition in general [28–31], focussing on the power sector and examining energy from biomass only roughly. Thrän et al. [37] investigated the allocation of biomass in different German energy sectors. The results show that wood based biomass in the transport and power sector is only competitive under special circumstances, expecting to have more competitive applications in the heat sector, which was not modelled in the mentioned study. To the authors' knowledge, there is no study modelling the complex structure of the complete heat sector in detail, while including hybrid heating technologies and representative bioenergy technology concepts, also in combination with other renewable technologies. Additionally, reviews focussing on model-based analysis in the heat sector, do not identify any studies combining the above mentioned research intentions [6,22].

In this paper, the cost-optimal allocation of biomass between different heat sub-sectors is investigated in the frame of long-term energy scenarios. The following research question is assessed:

- Which bioenergy technology concepts are competitive options in a future, climate target fulfilling heat sector and how does their potential role differ in different heat sub-sectors?

The aim of this investigation is to determine possible least cost system pathways towards a renewable heat supply and generate insights that inform policy makers about the future, cost-optimal use of biomass in the German heat sector.

2. Materials and method

In this study, the heat sector was divided into several sub-sectors, with different properties in terms of demand profiles and infrastructures. Representative bioenergy-, fossil- and other renewable (hybrid-)heat-technology concepts were defined for each sub-sector and the technological competition was optimized in the system within the framework of the German climate protection plan [9,12] in two scenarios. A consistent scenario framework was set up and detailed biomass feedstock data were defined, leading to a set of five biomass types, which can be processed into 20 biomass products. With additionally three fossil products, they can be applied to 47 different technology concepts. Within the model these technology concepts were in competition on 19 different sub-sectors to identify the optimal allocation of biomass in the heat sector.

2.1. Modelling

A mathematical optimization approach was chosen to model the heat sector. The approach of the model follows BENOPT (BioENergyOPTimisation model), which has been applied on the transport and power sector [25–27]. As a programming environment GAMS [14] is used in combination with MATLAB [36]. GAMS is an algebraic modelling language for mathematical optimization. In Matlab the input data is imported from Microsoft Excel [23], edited and automatically sent to GAMS, where the minimum costs are calculated. The results from the optimizer are exported back to Matlab, where they are evaluated and graphically prepared.

The model in this paper is fully deterministic and uses perfect foresight. The technology choice is optimized within the competition. It is a linear model, using the Cplex solver. The spatial boundary is Germany as a whole. The objective function is minimizing the total system costs over all technologies i, all sub-sectors s and the complete timespan $t = 2015 \ldots 2050$ (1). The total system costs are the sum of the technology specific marginal costs mc, multiplied with the amount of heat produced π, and the investment costs ic, discounted with the annuity method (discount rate q) [16], multiplied with the number of heating systems installed n^{cap}. In the model each (hybrid-)heat-technology concept is separated into different modules j, assigned with different lifetimes $\widehat{t}$ and individual investment costs.

Objective function

$$min \sum_{t,i,s,b} mc_{t,i,s,b} \cdot \pi_{t,i,s,b} + \sum_{t,i,j,s} ic_{t,i,j,s} \cdot n^{cap}_{t,i,j,s} \cdot \frac{q(1+q)^{\widehat{t_j}}}{(1+q)^{\widehat{t_j}} - 1} \tag{1}$$

subject to

$$\delta_{t,s} = \sum_{i,b} \pi_{t,i,s,b}, \ \forall (t,i,s,b) \in (T,I,S,B) \tag{2}$$

$$\varphi^{Res}_t + \Lambda^{Land}_t \cdot Y_{t,b} \geq \sum_{i,s,b} \dot{m}_{t,i,s,b}, \ \forall (t,i,s,b) \in (T,I,S,B_{bio}) \tag{3}$$

$$\varepsilon^{max}_t \geq \sum_{i,s,b} \alpha_{i,s} \cdot \left(\varepsilon^{rel}_{t,i,s} \cdot \pi_{t,i,s} + \varepsilon^{feed}_{t,i,s,b} \cdot \dot{m}_{t,i,s,b} \right), \quad \forall (t,i,s,b) \in (T,I,S,B) \tag{4}$$

$$\pi_{t,i,s,b} = \dot{m}_{t,i,s,b} \cdot \eta_{t,i,s}, \ \forall (t,i,s,b) \in (T,I,S,B) \tag{5}$$

$$n^{cap}_{t=2015,i,j,s} = n^{initial}_{i,j,s}, \ \forall (t,i,j,s) \in (T,I,J,S) \tag{6}$$

$$n^{cap}_{t+1,i,j,s} = n^{cap}_{t,i,j,s} + n^{ext}_{t+1,i,j,s} - n^{dec}_{t+1,i,j,s}, \ \forall (t,i,j,s) \in (T,I,J,S) \tag{7}$$

$$n^{dec}_{t,i,j,s} = n^{initialdec}_{t,i,j,s} + n^{extdec}_{t,i,j,s}, \ \forall (t,i,j,s) \in (T,I,J,S) \tag{8}$$

$$n^{extdec}_{t+\widehat{t_j},i,j,s} = n^{ext}_{t,i,j,s}, \ \forall (t,i,j,s) \in (T,I,J,S) \tag{9}$$

Marginal costs include feedstock costs (fossil or biomass), costs for power demand, maintenance and a CO_2-certificate price. The sum of these costs has a dynamic development, which depends on the time point, used technology, sub-sector and if applicable the consumed feedstock product b. Generated power in a combined heat and power (CHP) system is included as a credit within the variable costs. For details on how the credit is calculated see section 2.5.

The main model restrictions are as follows: First, the heat demand δ in each sub-sector needs to be fulfilled. Therefore the sum of the produced heat within one sub-sector equals the heat demand within a sub-sector in each year. Second, the yearly consumed biomass $\dot{m}$ within the system must not be higher as the sum of the limited biomass potential from residues φ^{res} and the limited land use potential Λ^{Land} multiplied with the corresponding yield Y of the energy crop. More details on the biomass potential and possible biomass pathways are explained in section 2.4 and 2.6. Third, the yearly maximal allowed amount of GHG emissions ε^{max}, representing the federal climate targets in Germany, must be greater or equal to the sum of the technology-based ε^{rel} and feedstock-based ε^{feed} emissions (4). The relationship between the produced heat and the utilised feedstock product is given in equation (5) and determined by the conversion efficiency η of each technology. Equations (6)–(9) explain the relationship between the number of heating systems installed (n^{cap}) at time point t, the number of heating systems newly invested in (n^{ext}) and the number of heating systems decommissioned (n^{dec}). The status quo of all installed heating systems in 2015 serves as a starting point ($n^{initial}$). This portfolio is linearly decommissioned over the corresponding lifetime of each technology ($n^{initialdec}$). Heating systems newly installed in the model (n^{ext}) are decommissioned after they have reached their lifetime, defined by the variable n^{extdec}. Premature decommissioning of heating systems is only allowed for fossil technologies and limited to 1%/a. As a restriction for energy crops, every type may maximally double its land use per year.

2.2. Heat sub-sectors

Heat utilisation differs from power utilisation, which is supplied through one uniform grid with a unique frequency and different voltage levels which can be transformed up and down. For heat supply, beside local heating grids, differing in temperature, pressure and extension, numerous single object solutions exist, with temperatures ranging from 1.000 °C for industrial processes down to low temperature heating with about 40 °C [40]. Additionally, the amount of heat required differs, with a corresponding capacity variation for heat generators. Furthermore, heating systems based on solid fuels (biomass, coal or waste) vary in terms of operation efficiency and emissions depending on the load [17]. Differing patterns for peak demand, yearly demand variations, temperature requirements and the relation between base load (e.g. hot water supply) and the varying proportion of the heat demand (e.g. space heating) require specially adapted technology concepts. Thus, heat demand can be divided into a whole series of sub-sectors in which different heating concepts have to be applied.

In reality, each heating object is individually examined and a decision on the best case is taken by the owner or an ordered decision maker according to an individual set of decision parameters and the knowledge of the involved actors. For an artificial model, a fixed set of decision parameters is required as well as a simplification of the decision cases (see section 2.1). Therefore, similar demand cases were aggregated to one sub-sector with mean values and a certain set up of suitable technology options. Special cases with low heat demands were included in the most suitable sub-sector.

The main difference in the heat supply depends on the required temperature level, which is basically distinguished between industrial applications (60 °C to more than 1.000 °C) and building heat demand (usually less than 95 °C). Considering comparable renewable heating concepts, industrial heat supply was separated into four sub-sectors by different temperature levels [18]:< 200 °C, 200–500 °C, 500–1.500 °C and one sub-sector for special coal demand (fossil or bio-coal) in industrial applications for steel production.

In addition to industrial applications, more than 50% of the total heat demand in Germany is used for space heating and hot water supply at a temperature level below 95 °C [40]. When supplying individual objects of different sizes with fossil systems, no major technological difference is required. A heat supply by bioenergy, however, requires the use of different technological solutions depending on the size of the boiler. From smaller applications in single family houses using stoves or wood log boilers, through pellet boilers in multi-family houses up to wood chip boilers in e.g. schools or hospitals, a variety of technological solutions and combinations are possible [17]. Additionally, CHP-technologies based on solid biomass fuels are favourable options for cases with a high base load demand, such as in indoor swimming pools. Considering these aspects, the private household and trade and commerce sector was structured into 14 sub-sectors according to the peak demand, the relation of hot water demand to total heat demand and the required temperature levels [21]. The future development of the heat demand in each sub-sector is based on the external results of the model 'B-STar' [19]. As a stocks exchange model, it represents the building stock in Germany and models the future refurbishment in different scenarios.

Centralized heating supply was summarized in one sub-sector, determined by the resolution of the data basis.

In total, 19 sub-sectors were defined and described, see Ref. [21]. The average thermal peak load demand and the annual final heat demand until 2050 serve as input data for the optimization model and the design of the different technology concepts in each sub-sector.

2.3. Technology concepts

In order to determine the future use of biomass in the heat sector, the market competition has to be depicted in the optimization model. Consequently, different fossil and renewable technological systems were selected for the competition in each sub-sector. Beside single technology solutions, also hybrid systems were included. Hybrid systems are combining different types of fuels, leading to a variety of possible technical solutions. For the final selection of the defined heating concepts, the following aspects were taken into account:

- The status quo of the national biomass feedstock mix and all installed heating systems in 2015 were considered.
- As the research is focused on biomass, at least one bioenergy heat concept as well as one bioenergy CHP concept, based on solid fuels, is integrated in each sub-sector.
- Solar thermal was integrated as an established technology on the market.
- One heat pump concept per low temperature sub-sector was defined, as this technology offers the potential to fulfil the complete heat demand for applications lower than 200 °C in a renewable way.
- In order to ensure a net renewable power supply for heat pumps, a heat pump concept is always designed in combination with a PV system, which produces the major share of the electricity demand over the year.

As the most competitive fossil references a gas boiler or gas boiler in combination with a solar thermal system as well as a gas fuel cell plus solar thermal system were defined in the most cases. Oil-fired boilers were not included in the modelling as they are more costly and emit more CO_2 equivalents than gas-fired boilers. Every gas-fired concept can either obtain natural gas or biomethane, which is fed into the gas network. Different single bioenergy solutions were described according to the amount of heat and the thermal peak demand. Additionally, bioenergy hybrid or multibrid systems including a heat-pump, solar thermal or PV were selected according to the heat demand parameters of the sub-sector. Future technical improvements were considered through yearly increase rates of thermal efficiency, electrical efficiency and a decrease in investment costs. For gasification systems, a change from combustion engines to fuel cells is considered within the next two decades.

In supplementary material it is shown which concepts are considered in which sub-sectors [21]. As there are some basic differences in the concepts between heating in buildings and industrial/district heating provisions, these two sectors are shown in separate tables. However, the allocation of biomass over the subsectors is treated equally.

In total, 42 technical concepts where described. The complete technical and economic data for each technology concept per subsector can be found in a published data set [21]. The calculated infrastructure emission factors of the single technology components as well as the feedstock specific emission factors can be found in supplementary material [21].

2.4. Feedstock data

According to the above described technology concepts, four main feedstocks are considered in this model to generate heat or combined heat and power. Biomass from residues and energy crops is used for all bioenergy technologies. The basis for all other renewable heat technologies is the usage of electricity and for the most competitive fossil technologies gas and coal have been chosen as a reference. The heat production from plastic waste has been set as a constant to the amount of generation in 2015. Details on fossil and power based energy prices are shown in Fig. 3.

The technical potential for biomass residues are shown until 2050 based on Brosowski et al. [7], shown in Fig. 1. Additionally, crops for energetic and material use are cultivated on 2.4 Mio ha of land in Germany today [5]. In this study, the maximum permitted land use is reduced linearly to 2.0 Mio ha in 2050, which is at the lower limit of identified values from currently available long-term energy scenario studies [28–31]. On this land area, ten types of energy crops are cultivated for heat and CHP applications today [5]. In Table 2 the applied yields and the status quo of land use for these crops in the year 2015 are attached.

Different prices arise for the defined feedstocks. A common method to estimate future prices of energy crops is to add the per hectare profit of a benchmark crop to the per hectare production costs of the energy crops [42]. In Germany, the most common crop is wheat [32], which holds for the benchmark crop in this study.

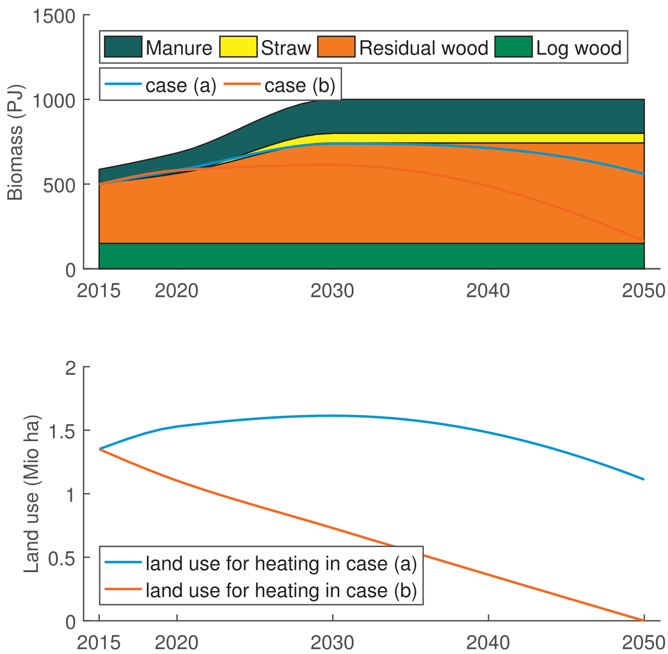

Fig. 1. Technical biomass potential from residues in Germany [7] (top). Available pre-allocated biomass potential and available land area in case (a) and (b) shown by the coloured lines. The model is free to pick from any category of residues and is free to cultivate any of the defined energy crops, as long as the defined upper scenario limit is not violated.

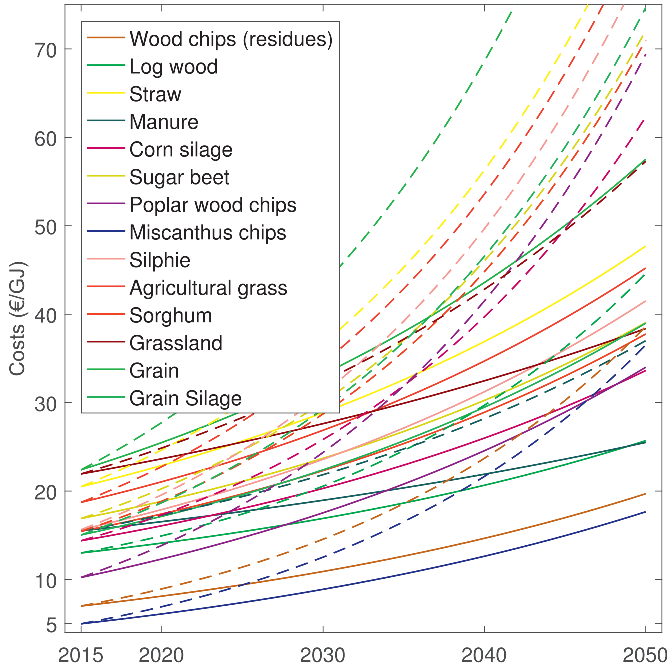

Fig. 2. Cost developments of the biomass feedstocks for a yearly wheat price increase of 3% (solid lines) and 5% (dotted lines).

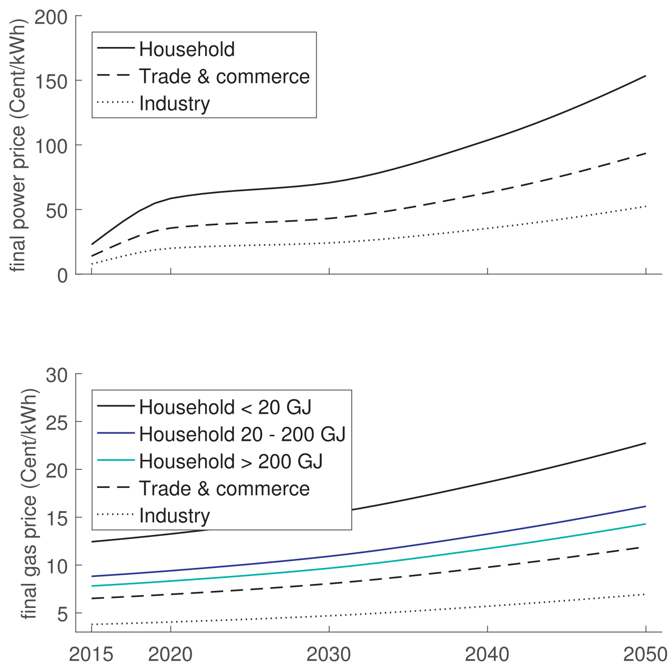

Fig. 3. End consumer power (top) and gas (bottom) prices. Own calculations based on Repenning et al. [11,30].

Based on the price increase of wheat in the last decades [43], two biomass price development scenarios are modelled in this study with a yearly increase of wheat by 3% and 5%. For a detailed description of the applied method in this paper the reader is referred to Ref. [24]. Prices for biomass products from residues in 2015 are according current prices [4,13,35]. For the future development, the yearly increase rate of wheat in the corresponding scenario is also applied to biomass residues. Fig. 2 shows the resulting price development of the considered biomass feedstocks.

Table 1
Model linkage of the heat sector to the power sector in terms of power consumed for heating and power use of CHP/PV technologies. The emissions from grid-based electricity are allocated to the heat sector in accordance to the power mix specific emission factor [30].

Power	Price	Credit	Heat sector emissions
external demand	Final consumer price	0	Emissions from grid power mix
internally used for heating	0	0	Emissions from techn. system
internally used for non heating	0	Final consumer price	0
fed into the grid	0	Stock market price	0

Table 2
Yield of the defined energy crops [20] and their corresponding land use in 2015 for heat or combined heat and power applications [5]. SRC = Short Rotation Coppice.

	Yield (GJ/ha)	Land use (ha) 2015
Corn silage	177	872 000
Sugar beet	150	15 600
Grain	91	151 000
Grain Silage	138	123 000
Agr. grass	137	20 150
Grassland	90	157 849
Silphie	126	400
Sorghum	152	0 (est.)
SRC	137	6630
Miscanthus	273	4500

Applied surcharges for extra processing steps, such as pelletising etc. can be found in Table 3.

Biomass from residues and energy crops can be converted into several secondary energy carriers. In this study, 20 biomass products and three fossil products have been defined. In supplementary material it is defined which products can be used in which technologies [21]. All fermentable feedstocks are processed into biomethane, which is fed into the gas supply network. Since multiple options per technology are possible, a differentiation between feedstock specific and technology specific emissions has to be made. In supplementary material an overview is given of the technology and feedstock specific emission factors and the corresponding allocation factors applied [21]. The emissions from grid-based electricity are allocated to the heat sector in accordance to the power mix specific emission factor [30].

2.5. Sector coupling

The heat sector is strongly linked to the power sector, especially when CHP and power to heat options are modelled. To generate conclusive results for the heat sector, a linkage to the power sector is inevitable. In order to achieve this linkage, a scenario framework was set up. Certain input parameters, such as the electricity price, the electricity-mix specific emission factor and the CO_2 certificate price, which are highly influential for the market development of the heat sector, do also rely strongly on the development of the power sector. These parameters and predicted fossil feedstock price developments are adopted from the 'KS95' scenario of the study of Repenning et al. [30]. Governmental subsidies, such as e.g. the EEG are not considered in this study. The only market steering instrument is the CO_2 price, which is applied on the complete heat sector. As a result, the linkage of the heat sector to the power sector in relation to power prices, feed-in tariffs, own electricity consumption and emission allocation is shown in Table 1.

Repenning et al. [30] projects the future development of power and gas prices for the energy only markets. The required end consumer prices for our investigations are calculated consumption-dependent according to the monitoring report of the federal network agency for the model starting year 2015 [11]. The future price developments are projected combining both sources [11,30], see Fig. 3.

2.6. Scenarios

In this study, a scenario of 95% GHG emission reduction compared to 1990 is analysed. The focus of the investigation lies on the development of biomass in the heat sector, but still considering the interactions to other energy sectors by setting a scenario framework, derived from the 'KS95′ scenario from the study of Repenning et al. [30]. From currently available long term energy scenarios in Germany [28–31], Repenning et al. [30] is the only one modelling a transformation path towards a 95% reduction scenario and also reaching this target in 2050. However, within the study of Repenning et al. [30] biomass is depicted in a rough level of detail and only a minor share of the available biomass potential is distributed to the heat sector in the 'KS95' scenario. In this paper, a broader range of biomass potential is pre-allocated to the heat sector. Szarka et al. [34] reviews the role of bioenergy in long-term energy scenarios. The allocation of biomass to the heat sector in 2050 varies strongly between the reviewed studies, ranging from $\sim 5-70\%$ of the overall potential.

Hence, two extreme scenarios are investigated in this paper, where one time a major share of the biomass potential (case a) and the other time a minor share of the biomass potential (case b) is pre-allocated for heating applications, for details see Fig. 1. Consequently, the biomass potential for heat applications is fixed for each year and scenario, but the model is free to pick from any category of

Table 3
Applied surcharges in the model based on own calculations.

	Surcharge (€/GJ)
Pellets compared to wood chips	5
Pellet torrefication	+14%
Briquettes compared to wood chips	7
Separator for torrefied poplar pellets in pellet technologies	0.3
Separator for miscanthus pellets in pellet technologies	0.2
Separator for poplar briquettes in log wood technologies	0.05
Separator for straw in wood chip technologies	0.4
Separator for poplar wood chips in wood chip gasification technologies	0.2
Separator for miscanthus chips in wood chip technologies	0.2
Transport fee for wood based feedstocks per delivery	50 €

residues and is free to cultivate any of the defined energy crops, as long as the defined upper scenario limit is not violated. In both scenarios, the actual status quo of national biomass use in 2015 serves as a starting point. Biomass imports are not allowed in order to avoid a shift of negative environmental effects abroad. For all scenarios, it is assumed that Europe and especially the neighbouring countries of Germany follow similar, ambitious climate targets and that no relocation of industries or imports arise. Carbon capture and storage (CCS) is not considered in this study.

Within the model a discount rate is considered for the investment costs. According to the recommendations of Steinbach [33], considering the methodology to derive social discount rates as well as discount rates used in analysed energy scenarios, the applied value in this model is set to 4%.

3. Results

In the following paragraph, a transformation path towards a 95% emission reduction in 2050 in the heat sector is shown. Modelling results are shown for cases (a) and (b) from 2015 to 2050. The market share of all technology types is shown in Fig. 4. As expected, the major market share shifts from natural gas technologies in 2015 to power based heat pumps in 2050. The share of bioenergy in the year 2050 is at 29.0% in scenario (a) and 5.7% in scenario (b). In both cases, the complete pre-allocated biomass potential is used up from the year 2035 onwards. The largest biomass shares are holding wood chip and pellet technologies. Additionally, in case (a), log wood technologies hold a constant market share of ~ 3%.

A more detailed illustration shows which biomass products are used for heating or CHP technologies, see Fig. 5. In 2015, one third of the utilised biomass was in the form of biogas, mostly based on corn silage. Without federal subsidies, as it is the case in this model, biogas production is not competitive and market shares decrease rapidly in both scenarios. A constant use of log wood over time is found in case (a), however, log wood technologies are the least cost competitive wood based bioenergy technologies, as their market share decreases rapidly with decreasing biomass potential in case (b) from 2030 onwards. In 2015 residual wood was mainly used for wood chip technologies. The model results show, that in a 95% emission reduction scenario the use of residual wood is most competitive over the next three decades in the form of pellets. However, in the last years until 2050, the use of residual wood in the form of wood chips is the favourable option to fulfil climate targets in a cost-optimal way.

The available land area for energy crops is cultivated with Miscanthus and processed to chips beginning after the decreasing cultivation of biogas feedstocks, see Fig. 5. Due to low feedstock costs and high yields, Miscanthus is a competitive option in such a scenario. Notable is the use of Miscanthus in form of chips in contrast to the use of residual wood in form of pellets.

Fig. 6 shows in which specific sub-sectors and technology concepts the biomass potential is distributed. In six sub-sectors, biomass technologies are competitive options in both scenarios. Five of these sub-sectors belong to the private household sector, in which pellet CHP and torrefied pellet CHP technologies in combination with a heat pump and a photovoltaic system are most competitive over the next three decades. However, between 2040 and 2050, with emission targets to be fulfilled and increasing power prices, a shift of biomass use towards high temperature industry applications is carried out. Consequently, pellet technologies are replaced by heat pumps or log wood technologies after their lifetime expansion.

The market share of log wood technologies is strongly dependent on the available biomass potential, as it is the least competitive wood based option. In case (a), with a high available potential, market shares are constant. Log wood achieves a share of ~ 80% in the 7,5 kW single family houses sector, where the log wood stove is combined with a heat pump and photovoltaic system, while in case (b) this technology holds only a minor market share.

To sum it up: in the trade and commerce sub-sectors none of the defined bioenergy technologies are a competitive option. Pellet-CHP and log wood technologies are favourable options in the private household sector, but only in combination with a heat pump and PV-system. Towards 2050, the use of residual wood is more cost efficient in high temperature heat applications.

4. Discussion

In this paper, the future role of biomass in a sustainable heat sector is investigated. First of all, the results show that a substantial emission reduction of 95% compared to 1990 is possible in the German heat sector. A reduction of 98%, as it is the case in other studies using 'backup capacities' [19,30], was not possible. Second, bioenergy is a competitive option within the defined scenario framework, which confirms the hypothesis from Thrän et al. [37–39] expecting to have more competitive applications for wood based biomass in the heat sector compared to the transport and electricity sector. Third, it is identified which biomass products are most competitive in which technology systems and on which subsectors of the heat sector.

According to the model results, in the next three decades until 2040–2045 biomass is identified to be most competitive in the private household sector, which is in line with Koch et al. [19] and Repenning et al. [30]. The most favourable options are

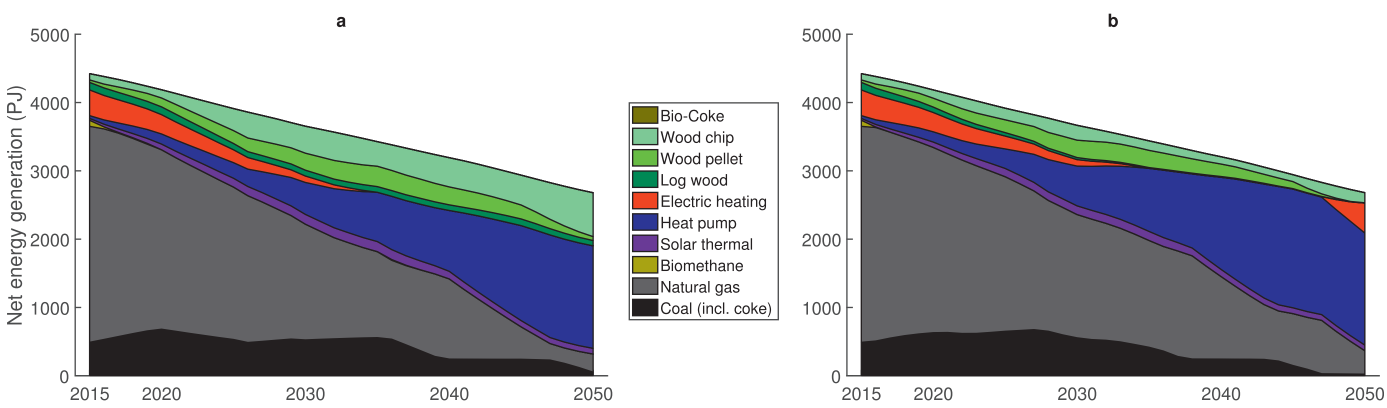

Fig. 4. Model resulting development of the technology market shares for the complete heat sector in case (a) and (b) in a yearly resolution.

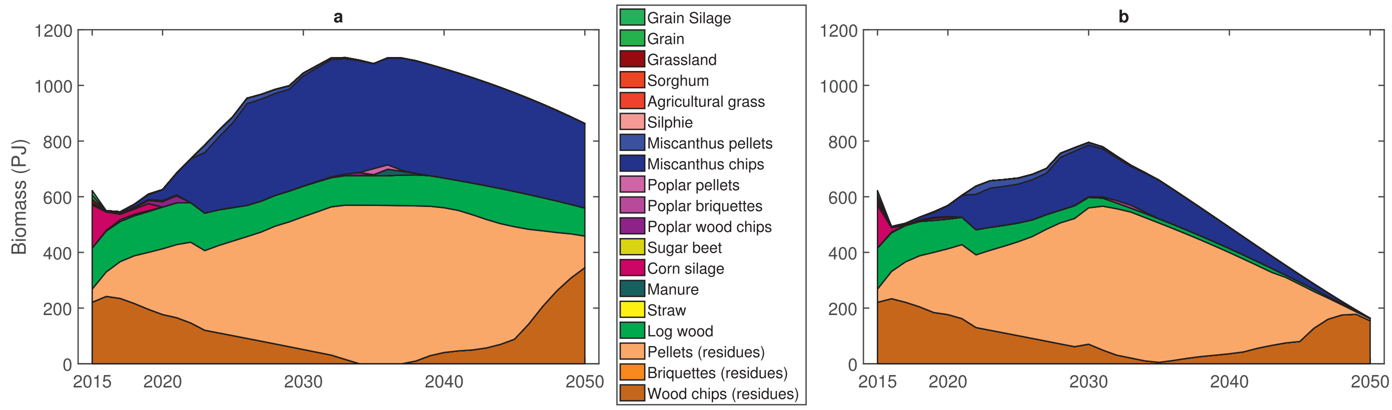

Fig. 5. Model resulting consumption of biomass products in case (a) and (b) in a yearly resolution.

decentralised hybrid CHP combustion applications using residual wood as feedstock. Especially the combination of a (torrefied-) wood pellet gasifier CHP with a heat pump and a PV-system is a favourable option. This is a unique finding in energy systems modelling. One reason for this finding is that in available studies on the German energy transition, bioenergy is only considered as single technology option and not analysed in hybrid heat systems [28–31,34]. Additionally, this finding shows that the future power price development has a strong impact on the competitiveness of heating systems. Fig. 7 shows the merit order of the prime costs for the most competitive biomass options and their corresponding competitors in selected sub-sectors for 2015, 2035 and 2050. With increasing power prices in 2035 and 2050 (see Fig. 3), hybrid heat technology systems develop to be the cheapest options of all. Despite these findings, hybrid systems seem to offer the highest degree of self-sufficiency and therefore being more resilient to any kind of feedstock price developments than the competing heating systems. Hence, we conclude that the synergies from hybrid heat technology systems and their GHG mitigation potential are highly underestimated and that such systems can substantially contribute to the success of the energy transition in Germany.

In the long term, in a 95% reduction scenario, bioenergy is most competitive in high temperature industrial applications in the form of wood chips. From 2040 to 2045 onwards, biomass use shifts almost entirely from the household sector to high temperature industry applications. This shift away from decentralised private households is in line with Koch et al. [19]. The use of wood based biomass for industry applications towards 2050 confirms the projections of several studies ([2,8,15,30,34]). Derived from the results, see Fig. 6, we conclude that with emission targets to be fulfilled in 2050 the sub-sector"'Industry >500 °C"' requires a major share of renewable technologies. Possible renewable options are heating from biomass or the use of electric arc furnaces. Prime costs of the electric arc are increasing strongly in 2050 compared to biomass heating or heat pumps, see Fig. 7. In the private household sector, the heat pump is an additional option, being more efficient and more cost effective than the electric arcs. Consequently, biomass use shifts to high temperature industry applications, avoiding the use of electric arcs. However, the benefits granted to industry, apart from the generally lower power prices (see Fig. 3), are not depicted in this model, making the electric arc a possibly cheaper option. On the other hand, the use of electric arcs requires significantly more renewable electricity capacity than the use of heat pumps, which, in contrast, also make use of ambient heat.

In the trade and commerce sector, as well as in district heating, biomass is not a favourable option. For district heating, biogas plants exist today as a result of federal subsidies in the last decades. Without this support, biogas shares are dropping rapidly in case (a) and (b), which is in line with findings from other studies in literature projecting the use of fermentable residues in the transport sector instead of the heat sector, [19,30,31,37].

From the results it is also found that available land for energy crops is cultivated with Miscanthus. Again, this is a unique finding in the modelling of the heat sector. While the cultivation of Miscanthus is an endogenous model result in this study, the above mentioned scenario analysis from literature set the type of energy crops as an input parameter. In addition, it is notable from our results, that Miscanthus is almost exclusively used as chips in industry applications. One explanation is that in private households additional costs for a separator are required if Miscanthus is used in pellet technologies. However, high yields and low production costs lead to a monopoly position among energy crops. So why does Miscanthus play only a minor role in agriculture today? [42] identify several major barriers, e.g. a lack of established markets, high establishment costs as well as uncertainties, arising to a large extent from the necessary long term commitment. These factors are not represented in our optimization model and must be considered separately. Nevertheless, to generate an indicator, a model run excluding perennial crops was performed, resulting in the use of biomethane from maize silage in high temperature industry applications in the long term.

Limitations: Modelling of the heat sector, as it is performed here, depends on several research studies serving as input data. Research insights may change, e.g. the potential of wood based residues was recently corrected downwards [3]. Do the results and conclusions change, when the pre-allocated biomass potential is changed? How would the results change if the share of the projected district heating network would be higher or if biomass allocation is optimized across all energy sectors? The scenario design with a higher and lower amount of biomass pre-allocated to the heat sector is supposed to represent such shifts of biomass use, but such an approach is limited. However, the outlined results in this study show the same tendency in both scenarios, indicating that these factors might have only a minor impact.

Of course, modelling has its limits, so does this model. The private household sector is depicted in a high level of detail, which was not possible for the industry and district heating sector, due to the limited available data basis. Further research in this direction is highly recommended from the authors' view.

As mentioned before, the power market is not modelled within this study. Therefore a new approach was established for linking the power and heat sector, see section 2.5. By setting a scenario framework it is not necessary to have a high temporal resolution, having the advantage of a short model run time leading to the

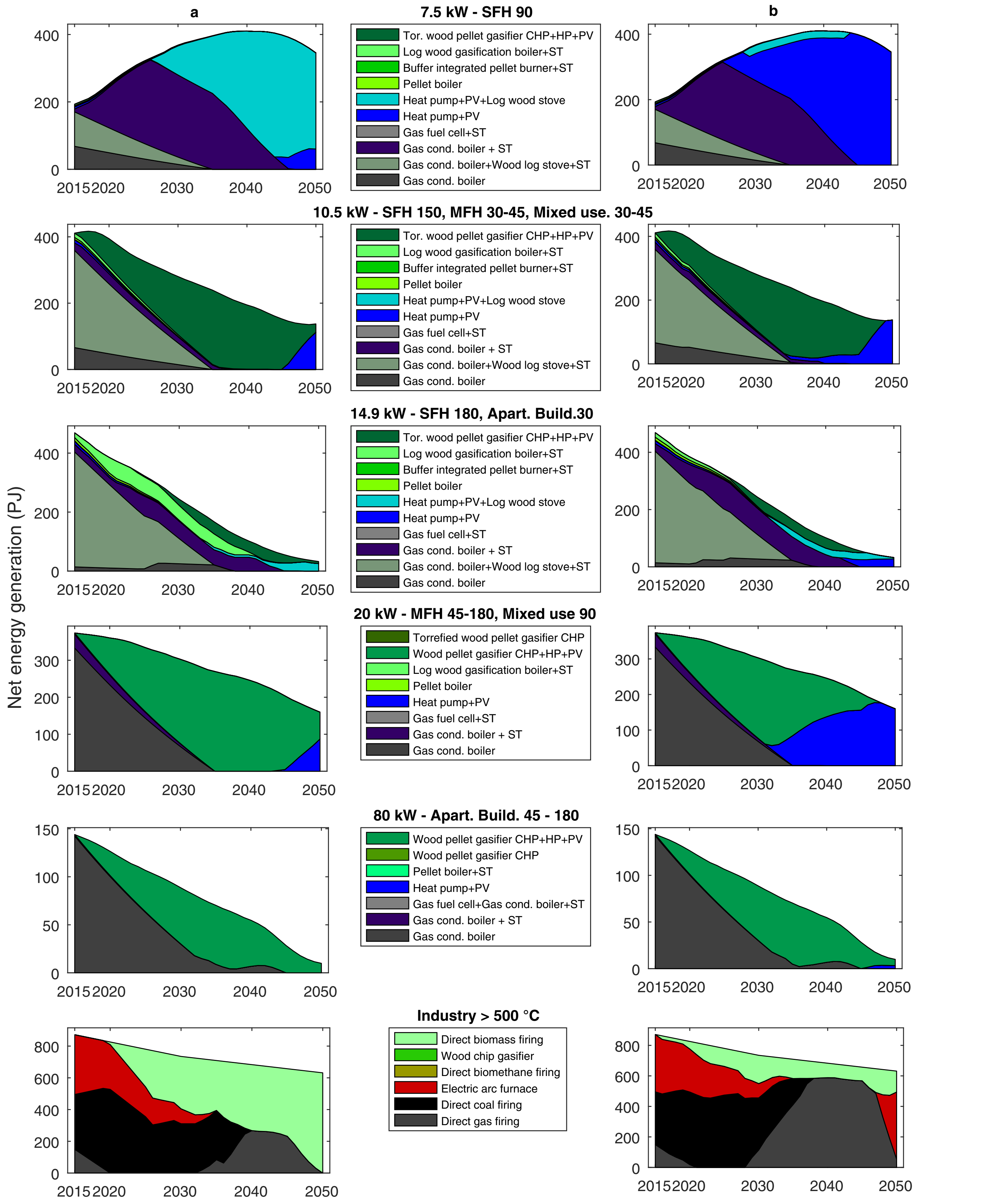

Fig. 6. Model resulting development of the technology shares in selected heat sub-sectors in case (a) and (b). The sub-sectors in which biomass technologies are most competitive are illustrated (6 out of 19). SFH = Single Family Houses; MFH = Multi Family Houses; ST = Solar thermal; PV = Photovoltaic; HP = Heat Pump; CHP = Combined Heat and Power.

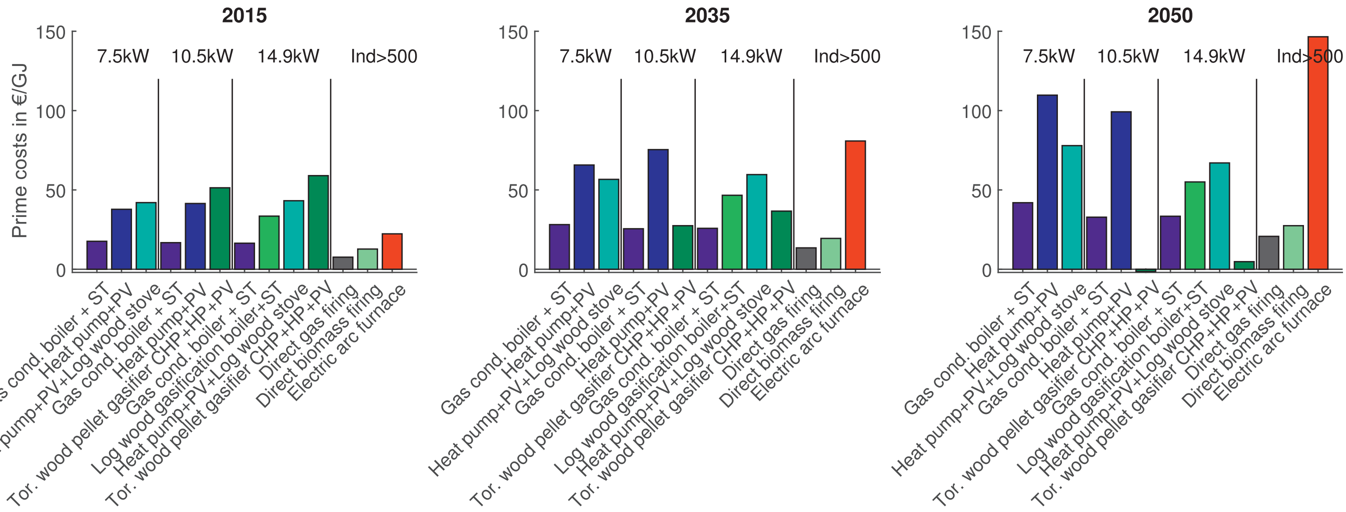

Fig. 7. Merit order of the most competitive biomass technologies and their corresponding competitors in selected sub-sectors for the years 2015, 2035 and 2050. Selected sub-sectors are from the private household sector 7.5 kW, 10.5 kW, 14.9 kW and Industry >500 °C. ST = Solar thermal; PV = Photovoltaic; HP = Heat Pump; CHP = Combined Heat and Power.

possibility to represent the heat sector and their technology concepts in more detail. To increase the annual resolution to a monthly one seems worthwhile to investigate, since the heat demand, PV yield etc. varies seasonally. However, our model results fit well into the results of the long-term energy scenarios in literature studies [19,28–31,34].

When future long-term modelling is done, uncertainties in the input parameters apply and have an effect on the model outcome. Using the applied model, with its short model run time compared to established energy scenario models, opens up the opportunity to apply a comprehensive sensitivity analysis. In future research we will implement all input parameters, having an uncertainty, into a sensitivity analysis and determine the effect of each parameter and all its interactions with all other parameters on the model outcome. A detailed description of the method and results goes beyond the scope of this article.

5. Conclusions

In this paper, a 95% reduction scenario is investigated with two extreme cases of available biomass potential. In both scenarios, the same trends develop, once in an attenuated and once in a stronger manner. It is found that emission targets in the heat sector can be fulfilled in both cases and bioenergy is found to be a future competitive option for heat applications. Especially hybrid heat technology systems were found to be extremely favourable. More specifically, the most cost efficient options for the next decades until 2040 were found to be in the private household sector in form of a hybrid CHP (torrefied-) pellet combustion plant in combination with a heat pump and a PV-system. A key driver for the competitiveness of these systems is the future development of power prices. In times of sector coupling, the advantages of such systems and their potential for emission reduction should not be underestimated and should be taken into account when designing policies. However, in the long term, wood based biomass use is found to shift almost entirely from the private household sector to high temperature applications in the industry. With increasing power prices, the use of wood chips from residues and energy crops in high temperature industry applications is found to be the most cost efficient way to reduce the heat based emissions by 95% in 2050.

Another finding from this study is, that available land for energy crops is almost entirely cultivated with Miscanthus. Despite several major barriers, arising to a large extent from the long term commitment, this finding should be discussed when designing policies.

Declaration of competing interest

None.

Acknowledgements

Thank you to Öko-Institut e.V. for sharing the heat demand data calculated with B-STar (Building Stock Transformation Model), which have been used in this study for the defined household, trade and commerce and district heating markets [19].

This work was funded by the Bundesministerium für Wirtschaft und Energie (03KB113B) and the Helmholtz Association of German Research Centers and supported by Helmholtz Impulse and Networking Fund through Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.17632/v2c93n28rj.2.

References

[1] Übersicht zur entwicklung der energiebedingten emissionen und brennstoffeinsätze in deutschland 1990-2016.
[2] Sektorkopplung – optionen für die nächste phase der energiewende.
[3] Dbfz - data repository. Ressourcendatenbank. 2019. http://webapp.dbfz.de/resources.
[4] agrarheute. Heu und strohpreise. 2018. https://www.agrarheute.com/markt/futtermittel/heu-stroh-preise-extrem-hohen-niveau-551055.
[5] Becker A, Peter D, Kemnitz D. Anbau und verwendung nachwachsender rohstoffe in deutschland. https://fnr.de/fileadmin/fnr/pdf/mediathek/22004416.pdf.
[6] Bloess Andreas, Schill Wolf-Peter, Zerrahn Alexander. Power-to-heat for renewable energy integration: a review of technologies, modeling approaches, and flexibility potentials. Appl Energy 2018;212:1611–26. https://doi.org/10.1016/j.apenergy.2017.12.073.
[7] Brosowski André, Adler Philipp, Erdmann Georgia, Stinner Walter, Thrän Daniela, Mantau Udo. Biomassepotenziale von Rest- und Abfallstoffen: status Quo in Deutschland. In: Schriftenreihe nachwachsende Rohstoffe. Fachagentur Nachwachsende Rohstoffe e.V. (FNR), Gülzow-Prüzen, vol. 36;

2015. https://www.bioliq.de/downloads/schriftenreihe_band_36_web_01_09_15.pdf.
[8] Thomas Bründinger, Julian Elizalde König, Oliver Frank, Dietmar Gründig, and Christoph Jugel. dena-leitstudie integrierte energiewende: Impulse für die gestaltung des energiesystems bis 2050 teil a: Ergebnisbericht und handlungsempfehlungen (dena) teil b: Gutachterbericht (ewi energy research & scenarios ggmbh).
[9] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Klimaschutzplan 2050 - klimaschutzpolitische grundsätze und ziele der bundesregierung: Kurzfassung. http://www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_kurzf_bf.pdf.
[10] Bundesministerium für Wirtschaft und Energie. Energiedaten: Gesamtausgabe. https://www.bmwi.de/Redaktion/DE/Downloads/Energiedaten/energiedaten-gesamt-pdf-grafiken.pdf?__blob=publicationFile&v=34.
[11] Bundesnetzagentur and Bundeskartellamt. Monitoringbericht. 2017; 2016. https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/DatenaustauschUndMonitoring/Monitoring/Monitoringbericht2016.pdf;jsessionid=907DA6C77633E11849D9FC3746057EC5?__blob=publicationFile&v=2.
[12] Bundesregierung. Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare energieversorgung. https://www.bundesregierung.de/ContentArchiv/DE/Archiv17/_Anlagen/2012/02/energiekonzept-final.pdf?__blob=publicationFile&v=5; 2010.
[13] C.A.R.M.E.N. e.V. C.a.r.m.e.n. e.v.. preisindizes. 2018. https://www.carmen-ev.de/infothek/preisindizes.
[14] GAMS Development Corp. Gams. 2019. https://www.gams.com/.
[15] Philipp Gerbert, Patrick Herhold, Jens Burchardt, Stefan Schönberger, Florian Rechenmacher, Almut Kirchner, Andreas Kemmler, and Marco Wünsch. Klimapfade für deutschland.
[16] Heuck Klaus, Dettmann Klaus-Dieter, Schulz Detlef. Elektrische Energieversorgung: Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis. 8 edition. Vieweg + Teubner; 2010.
[17] Kaltschmitt Martin, Hartmann Hans, Hermann Hofbauer, editors. Energie aus Biomasse: Grundlagen, Techniken und Verfahren. aktualisierte und erweiterte auflage edition, vol. 3. Berlin and Heidelberg: Springer Vieweg; 2016, ISBN 9783662474389.
[18] Kemmler Andreas, Straßburg Samual, Seefeldt Friedrich, Anders Natalia, Rohde Clemens, Fleiter Tobias, Aydemir Ali, Kleeberger Heinrich, Hardi Lukas, Geiger Bernd. Datenbasis zur bewertung von energieeffizienzmaßnahmen in der zeitreihe. 2005 – 2014.
[19] Koch Matthias, Hennenberg Klaus, Hünecke Katja, Haller Markus, Hesse Tilman. Rolle der bioenergie im strom- und wärmemarkt bis 2050 unter einbeziehung des zukünftigen gebäudebestandes. https://www.energetische-biomassenutzung.de/fileadmin/Steckbriefe/dokumente/03KB114_Bericht_Bio-Strom-W%C3%A4rme.pdf.
[20] Kuratorium für Technik und Bauwesen in der. In: Landwirtschaft eV, editor. Energiepflanzen: Daten für die Planung des Energiepflanzenanbaus. auflage edition, vol. 2; 2012.
[21] Lenz Volker, Jordan Matthias. Technical and economic data of renewable heat supply systems for different heat sub-sectors. 2019.
[22] Merkel Erik, McKenna Russell, Fehrenbach Daniel, Fichtner Wolf. A model-based assessment of climate and energy targets for the German residential heat system. J Clean Prod 2017;142:3151–73. https://doi.org/10.1016/j.jclepro.2016.10.153. ISSN 09596526.
[23] Microsoft. Mircrosoft excel. https://products.office.com/de-de/excel; 2019.
[24] Millinger M, Thrän D. Biomass price developments inhibit biofuel investments and research in Germany: the crucial future role of high yields. J Clean Prod 2016;172:1654–63. https://doi.org/10.1016/j.jclepro.2016.11.175. ISSN 09596526.
[25] Millinger M, Meisel K, Thrän D. Greenhouse gas abatement optimal deployment of biofuels from crops in Germany. Transp Res D Transp Environ 2019;69:265–75. https://doi.org/10.1016/j.trd.2019.02.005. ISSN 13619209.
[26] Millinger Markus. Systems assessment of biofuels. Modelling of future cost and greenhouse gas abatement competitiveness between biofuels for transport on the case of Germany. 2018. Leipzig, ISBN:1860-0387, http://nbn-resolving.de/urn:nbn:de:bsz:15-qucosa2-332464.
[27] Millinger Markus. Bioenergyoptimisation model. 2019.
[28] Nitsch Joachim, Pregger Thomas, Naegler Tobias, Heide Dominik, de Tena Diego Luca, Trieb Franz, Scholz Yvonne, Nienhaus Kristina, Gerhardt Norman, Sterner Michael, Trost Tobias. Langfristszenarien und strategien für den ausbau der erneuerbaren energien in deutschland bei berücksichtigung der entwicklung in europa und global: Schlussbericht. http://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf.
[29] Benjamin Pfluger, Bernd Tersteegen, Bernd Franke, Christiane Bernath, Tobias Bossmann, Gerda Deac, Rainer Elsland, Tobias Fleiter, André Kühn, Mario Ragwitz, Matthias Rehfeldt, Jan Steinbach, Andreas Cronenberg, Alexander Ladermann, Christian Linke, Christoph Maurer, Sebastian Willemsen, Benedikt Kauertz, Martin Pehnt, Nils Rettenmaier, Michael Hartner, Lukas Kranzl, Wolfgang Schade, Giacomo Catenazzi, Martin Jakob, and Ulrich Reiter. Modul 10.a: Reduktion der treibhausgasemissionen deutschlands um 95 % bis 2050 grundsätzliche überlegungen zu optionen und hemmnissen: Langfristszenarien für die transformation des energiesystems in deutschland - studie im auftrag des bundesministeriums für wirtschaft und energie.
[30] Repenning Julia, Emele Lukas, Blanck Ruth, Böttcher Hannes, Dehoust Günter, Förster Hannah, Greiner Benjamin, Harthan Ralph, Hennenberg Klaus, Hermann Hauke, Jörß Wolfram, Loreck Charlotte, Ludig Sylvia, Matthes Felix, Scheffler Margarethe, Schumacher Katja, Wiegmann Kirsten, Zell-Ziegler Carina, Braungardt Sibylle, Eichhammer Wolfgang, Elsland Rainer, Fleiter Tobais, Hartwig Johannes, Kockat Judit, Pfluger Ben, Schade Wolfgang, Schlomann Barbara, Sensfuß Frank, Ziesing Hans-Joachim. Klimaschutzszenario 2050: 2. Endbericht -studie im auftrag des bundesministeriums für umwelt, naturschutz, bau und reaktorsicherheit. https://www.oeko.de/oekodoc/2451/2015-608-de.pdf.
[31] Schlesinger Michael, Lindenberger Dietmar, Lutz Christian. Entwicklung der energiemärkte - energiereferenzprognose: Projekt nr. 57/12 studie im auftrag des bundesministeriums für wirtschaft und technologie. https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht.pdf?__blob=publicationFile&v=7.
[32] Statistisches Bundesamt. Land- und forstwirtschaft, fischerei: Landwirtschaftliche bodennutzung - anbau auf dem ackerland.
[33] Steinbach Jan. Modellbasierte Untersuchung von Politikinstrumenten zur Förderung erneuerbarer Energien und Energieeffizienz im Gebäudebereich. Dissertation. Fraunhofer-Institut für System- und Innovationsforschung and Fraunhofer IRB-Verlag; 2015.
[34] Szarka Nora, Eichhorn Marcus, Kittler Ronny, Bezama Alberto, Thrän Daniela. Interpreting long-term energy scenarios and the role of bioenergy in Germany. Renew Sustain Energy Rev 2017;68:1222–33. https://doi.org/10.1016/j.rser.2016.02.016. ISSN 13640321.
[35] TFZ. Entwicklung der brennstoffpreise. http://www.tfz.bayern.de/festbrennstoffe/energetischenutzung/035092/index.php; 2018.
[36] Inc. The MathWorks. Matlab; 2019. https://de.mathworks.com/products/matlab.html.
[37] Daniela Thrän, Oliver Arendt, Jens Ponitka, Julian Braun, Markus Millinger, Verena Wolf, Martin Banse, Rüdiger Schaldach, Jan Schüngel, Sven Gärtner, Nils Rettenmaier, Katja Hünecke, Klaus Hennenberg, Bernhard Wern, Frank Baur, Uwe Fritsche, and Hans-Werner Gress. Meilensteine 2030: Elemente und meilensteine für die entwicklung einer tragfähigen und nachhaltigen bioenergiestrategie.
[38] Thrän Daniela, Schaldach Rüdiger, Millinger Markus, Wolf Verena, Arendt Oliver, Ponitka Jens, Gärtner Sven, Rettenmaier Nils, Hennenberg Klaus, Schüngel Jan. The milestones modeling framework: an integrated analysis of national bioenergy strategies and their global environmental impacts. Environ Model Softw 2016;86(14–29). https://doi.org/10.1016/j.envsoft.2016.09.005. ISSN 13648152.
[39] Thrän Daniela, Arendt Oliver, Banse Martin, Braun Julian, Fritsche Uwe, Gärtner Sven, Hennenberg Klaus J, Hünneke Katja, Millinger Markus, Ponitka Jens, Rettenmaier Nils, Schaldach Rüdiger, Schüngel jan, wern Bernhard, Wolf Verena. Strategy elements for a sustainable bioenergy policy based on scenarios and systems modeling: Germany as example. Chem Eng Technol 2017;40(2):211–26. https://doi.org/10.1002/ceat.201600259. ISSN 09307516.
[40] Umweltbundesamt. Energieverbrauch Für fossile und erneuerbare wärme. https://www.umweltbundesamt.de/daten/energie/energieverbrauch-fuer-fossile-erneuerbare-waerme#textpart-1.
[41] Umweltbundesamt. Erneuerbare energien in zahlen. 2017. https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#textpart-1.
[42] Witzel Carl-Philipp, Finger Robert. Economic evaluation of miscanthus production – a review. Renew Sustain Energy Rev 2016;53:681–96. https://doi.org/10.1016/j.rser.2015.08.063. ISSN 13640321.
[43] World Bank. Global economic monitor (gem) commodities: Wheat. hrw; 2019. databank.worldbank.org.

Paper 2

Robust bioenergy technologies for the German heat transition: A novel approach combining optimization modeling with Sobol' sensitivity analysis.

Jordan, M., Millinger, M. and Thrän, D.

Applied Energy (2020), 262, art. 114534

Applied Energy 262 (2020) 114534

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Robust bioenergy technologies for the German heat transition: A novel approach combining optimization modeling with Sobol' sensitivity analysis

Matthias Jordan[a,c,*], Markus Millinger[a], Daniela Thrän[a,b,c]

[a] Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany
[b] DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Strasse 116, 04347 Leipzig, Germany
[c] University Leipzig, Institute for Infrastructure and Resources Management, Grimmaische Str. 12, 04109 Leipzig, Germany

HIGHLIGHTS

- Future power and gas prices drive the competitiveness of bioenergy technologies.
- Solid biomass in (high temperature) industry applications is the most robust option.
- With rising power prices hybrid CHP pellet technologies are competitive options.
- The applied method leads to policy insights with a high level of confidence.

ARTICLE INFO

Keywords:
Heat sector
Bioenergy
Optimization
Sensitivity analysis
Sobol'

ABSTRACT

Uncertainties are one of the major challenges of energy system optimization models (ESOM), yet little use is made of systematic uncertainty assessments in ESOM-based analyses. In this paper, an ESOM is combined with the global sensitivity analysis of Sobol' to identify robust, competitive bioenergy technologies to fulfill the climate targets in the German heat sector under uncertain developments. Through the outlined method, only three out of 32 investigated parameters were identified to have uncertainties with significant impacts on the future competitiveness of bioenergy technologies: the power price, gas price and the defined climate target. Based on these findings, a solution space is quantified showing which bioenergy technologies are robust, competitive options under the uncertainty of the three influencing parameters. The use of biomass in the form of wood chips in (high temperature) industry applications is found to be the most robust choice in all cases, while hybrid combined heat and power wood pellet systems are an additional robust option when future power prices are increasing. Both technologies have the potential to close gaps in a sustainable energy system and should be considered for the future use of biomass in the German heat sector, when designing policies.

1. Introduction

Climate change requires a transition of national energy systems away from fossil fuels to renewable solutions. In the case of Germany, emissions are to be reduced by 80–95% compared to 1990. A major share of that reduction needs to be covered by renewable heat solutions, which provided only 14% of the German heat demand in 2018 [1]. Bioenergy was the largest renewable heat contributor, but its potential is limited and its future use is uncertain. Therefore, insights need to be generated that inform policy makers about the cost-optimal use of bioenergy in a sustainable German heat sector under uncertain developments.

To determine possible least cost system pathways towards a renewable energy supply, ESOMs are widely used. Calculated model results are diverse and often lead to different recommendations. A major criticism of this approach is that the models are shaped by factors which are deeply uncertain [2], including e.g. technology innovation, resource availability, future feedstock price developments and socio-economic dynamics. Similar uncertainties arise in the German energy or heat sector and need to be considered when applying ESOMs to inform policy makers. Accordingly, possible methods that can address these issues need to be evaluated.

Two types of uncertainties can be distinguished for ESOMs [3]: parametric and structural. Parametric uncertainty refers to imperfect knowledge of ESOM input values. Structural uncertainty refers to the imperfect mathematical relationships within the model. To address

* Corresponding author at: Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany.
E-mail address: matthias.jordan@ufz.de (M. Jordan).

https://doi.org/10.1016/j.apenergy.2020.114534
Received 8 October 2019; Received in revised form 9 January 2020; Accepted 12 January 2020

these limitations, uncertainty assessments can be applied. Yue et al. [4] outline a review of approaches to uncertainty assessment in ESOMs. The majority of over 2000 studies associated with ESOMs have been used in a deterministic fashion with limited attention paid to uncertainty. About 100 studies used a scenario analysis to address uncertainty and only 34 studies performed a systematic uncertainty assessment. Scenario analysis is one of the simplest ways to explore the decision landscape under alternative futures. It has been criticized, e.g. as "black-box" due to its lack of transparency [5], as a deterministic methodology not suitable for complex problems with inherent uncertainties [6] and as a method that underestimates the range of possible outcomes [7]. Within best practice formulations for ESOMs, DeCarolis et al. [2] recommends performing a systematic uncertainty assessment to quantify uncertainty wherever possible. A systematic assessment can test the robustness of the model results by identifying which parameters drive the model outputs and help focus scenario analyses [2]. Today only a few studies follow these recommendations [8–11].

Yue et al. [4] identified four prevailing approaches that have been applied to systematically assess uncertainty in ESOMs: Monte Carlo analysis (9 findings), stochastic programming (18), robust optimization (3), and modeling to generate alternatives (4). Each of the four techniques has its own focus, advantages and limitations. In principle, Monte Carlo analysis varies the uncertain input parameters over a probability distribution. The resulting collection of model outputs can then be evaluated statistically using a global sensitivity analysis. The combination of Monte Carlo and global sensitivity analysis can address both parametric and structural uncertainty. It is a powerful technique compared to the other approaches addressing uncertainty, but it suffers heavily from computational burden. It requires hundreds to thousands of model evaluations, making it impractical for complex models with a long model run time. However, DeCarolis et al. [2] recommends applying Monte Carlo/global sensitivity analysis, as a best practice wherever possible to test the robustness of model results and insights.

Variance-based, global sensitivity analyses, also known as Sobol' methods, are versatile. They are well suited for taking input factor interactions into account and have established themselves among practitioners in many scientific fields [12–14]. However, to the authors' knowledge, it has not yet been applied to ESOMs. The only similar approach applies the Morris screening method on energy models, which performs local sensitivity analyses in a global context, and is computationally less demanding [10,9]. In this study, a method is performed to identify uncertainties in ESOM results by combining optimization modeling with the global, variance-based sensitivity analysis of Sobol'. The majority of parameters, all having uncertainties within their future development, are investigated. The effect of each parameter and its interaction with the other parameters on the model outcome is determined. Based on the identified, significantly influential input parameters, a solution space for technology competitiveness is generated. This approach is computationally expensive, but purposeful when aiming to quantify uncertainty. As mentioned above, limited attention is paid to uncertainty in ESOMs and a need for practical methods to quantify uncertainty exists. The method in this paper can serve as a case study for ESOM's with a model run time in the range of minutes and can theoretically be applied to any ESOM or region.

In this case, the outlined method is applied to a model optimizing the future use of biomass in the German heat sector [15,16]. In former studies, various scenarios were calculated with this model to identify competitive bioenergy technologies in a future heat sector, fulfilling the climate targets. The chosen model is set up with a high level of detail in regard to technical and economic input data, but is still well suited for a quantitative sensitivity analysis, as the model run time is in the range of one minute, which is crucial to perform a quantitative sensitivity analysis [17].

Biomass has advantageous properties compared to other renewable resources, such as weather independency, simple storage and flexible utilization, which open up a wide field of applications for biomass. However, biomass is limited and its future use in order to fulfill the greenhouse gas (GHG) reduction targets in the German heat sector is uncertain and to be investigated in this paper by assessing the following research questions: Which bioenergy technology concepts are robust, cost-competitive solutions for fulfilling the climate targets in a future German heat sector? Which factors are significantly influential for the cost competitive future use of bioenergy? In this study, a comprehensive sensitivity analysis and thereby a quantifiable solution space for the future role of biomass in the German heat sector is identified in order to improve the robustness of the outputs from optimization modeling and their use in providing policy insights.

2. Materials and method

2.1. The optimization model

The optimization model was used in former research to determine the future, cost optimal use of biomass in the German heat sector under different long term climate mitigation scenarios [15,16]. In this study, the same model formulations are used, but all input parameters are not set according to a certain scenario. Instead, a probability distribution of the parameter uncertainties is systematically assessed.

The model structure is as follows: The three main sectors of the German heat sector, private household, industry and trade/commerce are further divided into several sub-sectors, with different properties in terms of demand profiles and infrastructures. In total, 19 sub-sectors were defined and described. The future development of the heat demand in each sub-sector is based on the external results of the building stock model 'B-STar' [18], which models the future refurbishment of the German building stock in a yearly resolution using an agent based approach. Within the optimization model, for each sub-sector, representative bioenergy-, fossil- and other renewable (hybrid-) heat technology concepts are described [19], incl. e.g. gas boiler, heat pumps, direct electric heating, solar thermal, log wood, wood pellet and wood chip technologies. Possible feedstocks for each technology are defined. In total 20 biomass products (incl. wood based residues, log wood, straw, manure, two perennial crops and seven types of energy crops) and 3 fossil feedstocks are possible inputs, see supplementary data [19]. For the single technology components, infrastructure emissions as well as the feedstock specific emissions are considered within the model.

The technological choice is optimized between 2015 and 2050 in a yearly resolution, while fulfilling the German climate mitigation targets [20,21]. The objective function is minimizing the total system costs over all technologies, sub-sectors and the complete time span, using the Cplex solver for the linear problem. The spatial boundary is Germany as a whole and the sectoral coverage exclusively includes the heating sector. A consistent framework was set up representing the linkage to the power sector. For a detailed description of the model formulations, the linkage to the power sector, the definition of the sub-sectors and technology concepts as well as the possible feedstock and technology pathways the reader is referred to [15]. Detailed economic and technical data of the technology concepts can be found in supplementary data [19].

2.2. Assessment of parameter uncertainty

From the input data of the optimization model, parameters with a possible uncertainty in their future development were selected for the uncertainty assessment. The choice whether a parameter is attached with a future uncertainty was based on expert elicitation. Table 1 shows the selected 32 parameters and the range in which the parameters were varied for the sensitivity analysis. Information on the uncertainty range of the parameters was obtained through existing studies or expert elicitation.

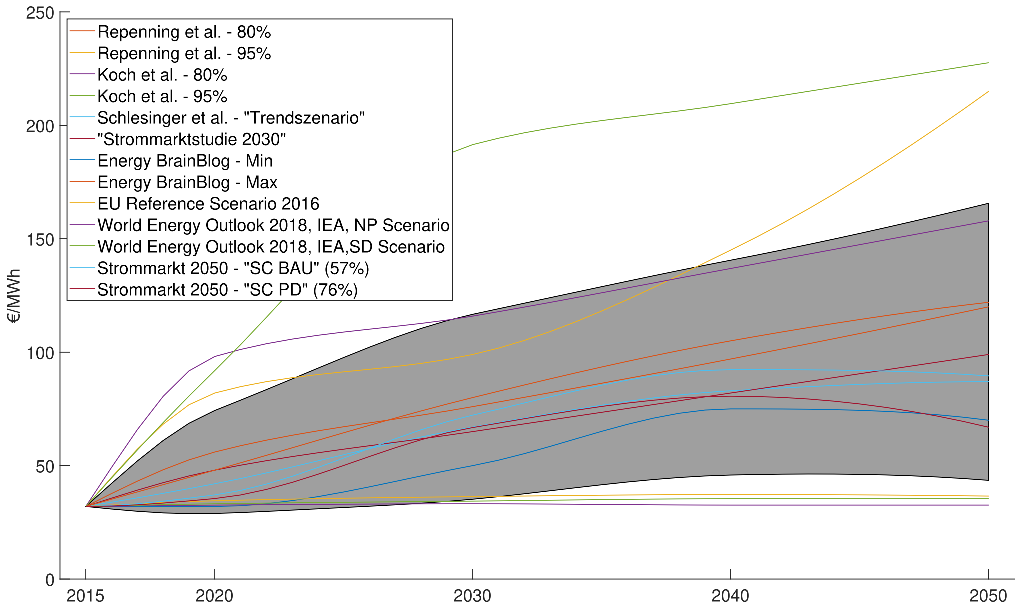

Fig. 1. Development curves of the future electricity-only market prices according to existing scenario studies [33,18,34–39]. The investigated uncertainty range of the power price development in this study (grey area) is defined by the mean of all curves ± the according empirical standard deviation.

In seven cases, parameter values are not static, but dynamically changing over time and their uncertainty is increasing with progressing time, as e.g. in future feedstock price developments. Fig. 1 exemplarily shows the development of the future electricity-only market price according to 12 different scenario studies. The investigated uncertainty range of the power price development in this study (grey area) is determined by calculating the mean of the 12 scenarios ± the corresponding empirical standard deviation. Within this uncertainty range (grey area), price development curves are sampled and assessed within the sensitivity analysis. The uncertainty range of the other parameters dynamically changing over time is determined using the same method.

Apart from the 32 parameters in Table 1, future uncertainty is also attached to the heat demand development and depends on the refurbishment rate of the different sub-sectors. The data used for the heat demand development in the optimization model is adopted from an external source and only available for an 80% and 95% GHG reduction scenario [18]. Consequently, it is not purposeful to sample curves within an uncertainty range. Instead, the heat demand development is linked to the GHG reduction target. In cases of $80 - 87.5\%$ GHG reduction in 2050, the heat demand development data set of the 80% scenario is adopted. For higher GHG reductions in 2050, the data set of the 95% scenario is applied.

The future availability of biomass in general and particularly for heating purposes also has uncertainty. In the DBFZ resource data base [22] current biomass usage and unexploited potential from residues is investigated for over 80 types of residues. Within this data base, maximal and minimal values for every type of residue is defined, based on a consistent comparison of existing findings from literature [23]. This data, combined with energy conversion factors [24,25] and the yearly available potential of log wood [26], serve as a basis for our investigation. The uncertainty span for the available biomass potential from energy crops is sampled along a defined range (2.4 mio ha in 2015; 0–2 mio ha in 2050). From this potential, a certain share of the available biomass potential is pre-allocated to the heat sector. This pre-allocation is deeply uncertain and sampled along a range, starting with the actual amount of biomass used for heat in 2015 towards 30–70% of the available potential in 2050. This range is derived from the review by Szarka et al. [27], which shows the projected spread of future biomass usage over the German energy sectors in various energy scenarios. The uncertainty of the biomass potential and the biomass potential pre-allocated for heating purposes is analyzed as a whole and not separately for each biomass product.

2.3. Sensitivity analysis

In this paper, the variance-based sensitivity analysis of Sobol' was applied to systematically assess which uncertain input factors are responsible for the uncertainty in the model output. When aiming to quantify the relative importance of input parameters $p = 1..k$ for determining the value of an assigned output variable $f(p)$, variance-based methods are proven versatile and effective among the various available techniques for sensitivity analysis of model outputs [12]: "Unlike experimental design, where the effects of factors are estimated over levels, variance-based methods look at the entire factors distribution, using customarily Monte Carlo methods of various sophistication.".

Sobol' sensitivity analysis studies the scalar model output $f(p)$ if the model parameters are varied within their uncertainty range. After N model runs with different parameter sets, the variance $V = V(f(p))$ of the scalar output $f(p)$ is split into component variances V_i from individual parameters or parameter interactions. The first order model sensitivity to each parameter p_i is quantified with the first-order Sobol' index S_i, also known as the main effect. The total-order Sobol' index S_{Ti} represents the total effect of parameter p_i and its interaction with all other parameters. A more detailed description of the Sobol' method and how to apply it on models can be found in Saltelli [17], Saltelli et al. [12].

In this study, an algorithm was chosen to calculate the Sobol' main effect and total effect with $N(k + 2)$ model evaluations [17]. The method used to calculate the Sobol indices requires two independent matrices A and B both containing N sets of k parameters. In this case, k is the number of parameters and N is the sample size used for the random value estimate for parameters being varied. For the random value estimate, Cuntz et al. [28] recommends the use of e.g. stratified sampling such as latin hypercube sampling, which was applied in this study with a sample size of $N = 1000$. The latin hypercube sampling technique evenly samples from the probability distributions [29]. The additionally required matrix $A_B^{(i)}$ has all columns of $A(B)$ except the i^{th} column, which comes from B(A). The exact formulation of the indices S_i and S_{Ti} are chosen from Table 2(b), (f) of Saltelli et al. [12], which are described as being *best practice*.

Table 1
Assessed input parameters and their defined uncertainty range. A variation of ± is compared to the initial value in Jordan et al. [15]. The heat demand development is adopted from an external source [18] and linked to the GHG reduction target. PMEF = power mix emission factor

Parameter range	Min in %	Max in %	Source
Power price in €/MWh	32.0 → 43.5	32.0 → 165.6	[33,18,34–39]
Gas price in €/MWh	19.8 → 24.6	19.8 → 42.6	[37,38,33,40,18,41,34,42,43]
Coal price in €/MWh	9.4 → 9.0	13.3 → 23.3	[37,38,33,40,18,41,34,42]
CO_2 cert. price in €/tCO_2equiv.	10.9 → 17.8	17.7 → 286.5	[37,38,33,40,18,41,34,42–45]
PMEF in gCO_2equiv./kWh	564.8 → 12.7	585.9 → 96.5	[33,46,18,34,41,47,48]
Increase of biomass prices in %/a	1	5	Derived from historical data
Discount rate	1	7	Steinbach and Staniaszek [49]
GHG reduction target	80	95	'Energiekonzept' [21]
Biomass potential	see Section 2.2	see Section 2.2	DBFZ - Data repository [22]
Bio. potential pre-allocated to heat	act. use → 30	act. use → 70	Derived from Szarka et al. [27]
Yield energy crops combustion	−33	+33	Derived from KTBL [50]
Yield energy crops digestion	−20	+20	Derived from KTBL [50]
Emission factors biomass feedstocks	−30	+30	Expert elicitation
Emission factors fossil feedstocks	−10	+10	
Investment wood chip tech.	−10	+10	
Investment wood pellet tech.	−10	+10	
Investment log wood tech.	−10	+10	
Investment electric heating	−10	+10	
Investment heat pump tech.	−10	+10	
Investment solar thermal tech.	−10	+10	
Investment gas tech.	−10	+10	
Lifetime wood chip tech.	−5	+5	
Lifetime wood pellet tech.	−5	+5	
Lifetime log wood tech.	−5	+5	
Lifetime electric heating	−5	+5	
Lifetime heat pump tech.	−5	+5	
Lifetime solar thermal tech.	−5	+5	
Lifetime gas tech.	−5	+5	
Conversion efficiency wood chip tech.	−5	+10	
Conversion efficiency wood pellet tech.	−5	+10	
Conversion efficiency log wood tech.	−5	+10	
Conversion efficiency biogas	−5	+10	

$$S_i = \frac{1}{V}\left[\frac{1}{N}\sum_{j=1}^{N} f(B)_j(f(A_B^{(i)})_j - f(A)_j)\right] \quad (1)$$

$$S_{Ti} = \frac{1}{V}\left[\frac{1}{2N}\sum_{j=1}^{N} (f(A_B^{(i)})_j - f(A)_j)^2\right] \quad (2)$$

Both Sobol' indices range from 0 to 1. $S_{Ti} \geqslant S_i \geqslant 0$. If $S_{Ti} = S_i = 0$ the parameter is non-influential. If $S_{Ti} = S_i$ there is no interaction of the i^{th} parameter with other parameters.

The scalar model output $f(p)$, on which the Sobol' indices are applied to in this study, is defined by calculating the share of the consumed biomass $\dot{m}$ of each biomass product b in relation to the sum of all biomass products used for heating. In each case, the biomass was summed over the complete time span t = *2015–2050*.

$$f(p = 1..k) = \frac{\sum_{t=2015}^{2050} \dot{m}_{t,b}}{\sum_{t=2015}^{2050}\sum_{b=1}^{20} \dot{m}_{t,b}}$$

The optimization model is evaluated $N(k+2) = 34000$ times. To overcome the computational burden, the calculations were executed on a model server grid with 32 cores having 64 logical processors, using 140 GB of RAM in peak and 34 optimizations running in parallel. The total calculation time took ~60 h.

A visual depiction of how the Sobol' method is applied to the ESOM can be found in Fig. 2. Based on the significance of the calculated Sobol' indices, scatter plots and min/max plots are generated to further analyze how the significantly influencing input parameters impact the model outcome $f(p)$. Based on this analysis, a solution space is quantified for the future cost-optimal use of biomass in the German heat sector under uncertain developments.

3. Results

3.1. Results from sensitivity analysis

For 16 out of the 20 defined biomass products the share $f(p)$ was <3% in 95% of the 34000 model evaluations. For 12 products, the share was even <1% in 99% of all model runs. Consequently, the market shares of 16 biomass products were considered unrelevant and the sensitivity assessment was further investigated on only four of the 20 biomass products, which are:

- Wood chips (from residues)
- Wood pellets (from residues)
- Log wood
- Miscanthus chips

These four biomass products use >90% of the available biomass potential in 98.8% of the model runs and >95% of the available biomass in 92.7% of the model runs.

The calculated Sobol' indices for the four relevant biomass products are shown in Fig. 3. It is found that 24 of the 32 investigated parameters are non influential to the defined model output and only 8 parameters have an impact on the competitiveness of the biomass market shares. Due to the significant difference in the values of S_{Ti} to S_i of the parameters "power price" and "gas price", an interaction of these two parameters can be identified. However, from the Sobol' indices and the parameter interactions it cannot be analyzed how the 8 parameters impact the model output f(p). Therefore, scatter plots were generated for each Sobol' index with a value >0.05. Input/output scatter plots are a simple and informative way to provide an immediate visual depiction of the relative importance of the parameters [30]. More shape or pattern in a scatter plot indicates that f(p) is more sensitive to the corresponding parameter. A high penetration over a wide range of outcomes

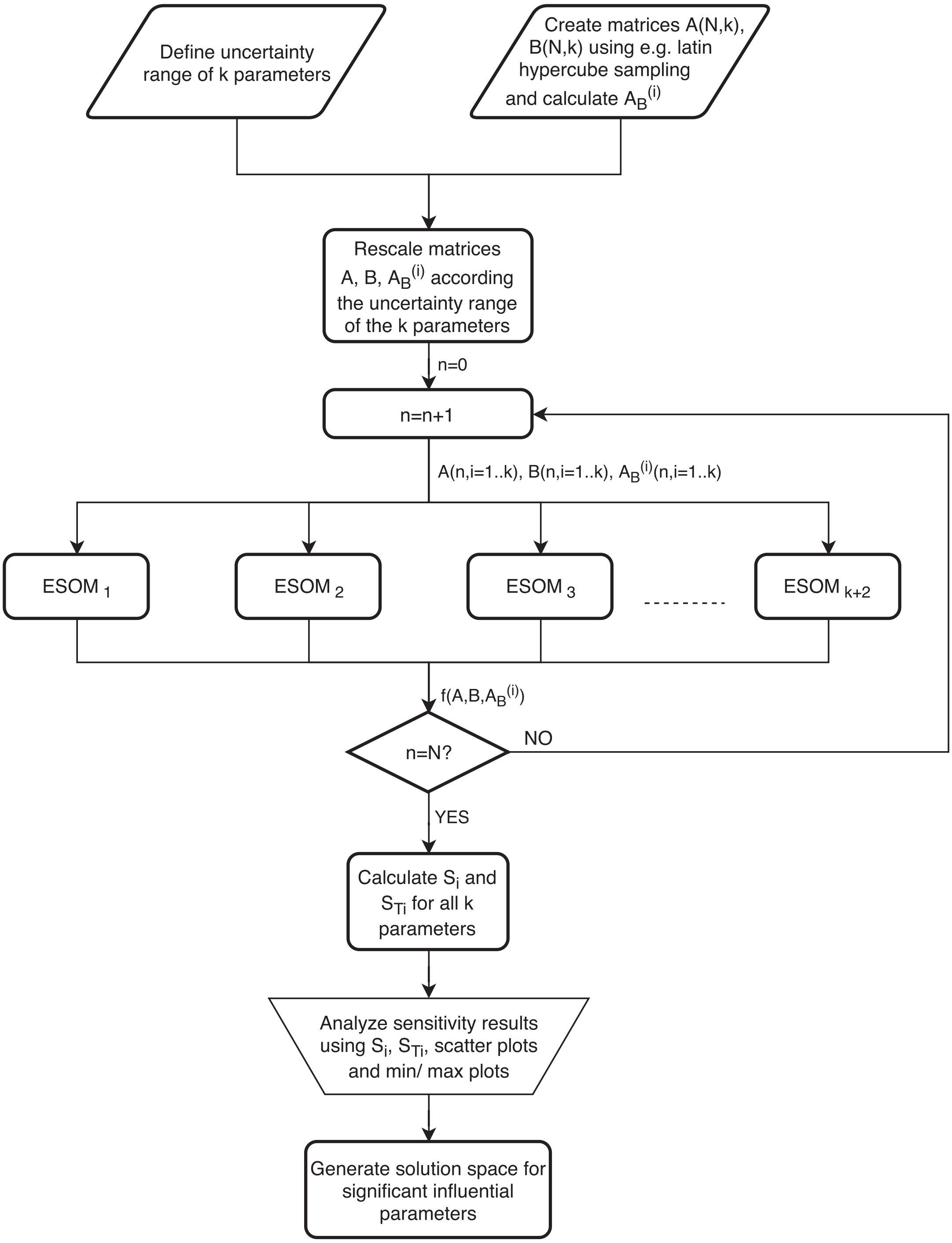

Fig. 2. Flow chart illustrating how the Sobol' method is applied to the ESOM and how further analyses are conducted in this study. $ESOM_{1..k+2}$ have the exact same model formulations, only the input parameters are varied according to the Sobol' method. The flow chart shows one possibility to overcome the computational burden by applying parallel computing.

is a strong indication of robustness [31,4].

In 12 of 18 scatter plots a pattern could be identified, affecting 7 parameters, see Figs. 4 and 5. From the Sobol' indices as well as from the scatter plots, it is found that the uncertainty in the future power price development has the greatest impact on the share of wood chips and wood pellets, which in most cases hold the greatest market shares. High power prices favor wood pellet market shares, while low power prices favor wood chip market shares. In the scatter plot of Fig. 4, it is found that the power price influences the upper and lower bounds of the product shares, indicating that this parameter affects the choice of the biomass product. While e.g. the uncertainty of the parameter "biomass potential" only affects an upper or lower bound, indicating that the parameter does not affect the choice of the product, but does have amplifying effects.

The log wood shares are significantly influenced by four parameters, but only in a minority of the cases. In only 5.7% of all model runs, product shares of log wood rise up to 20–45%, mainly influenced by low power prices and high gas prices. This confirms the findings from the Sobol' indices that the parameters "power price" and "gas price" are interacting. High log wood market shares only apply when power prices are low and gas prices are high. A variation of only one of the parameters does not lead to this result. However, the low penetration for

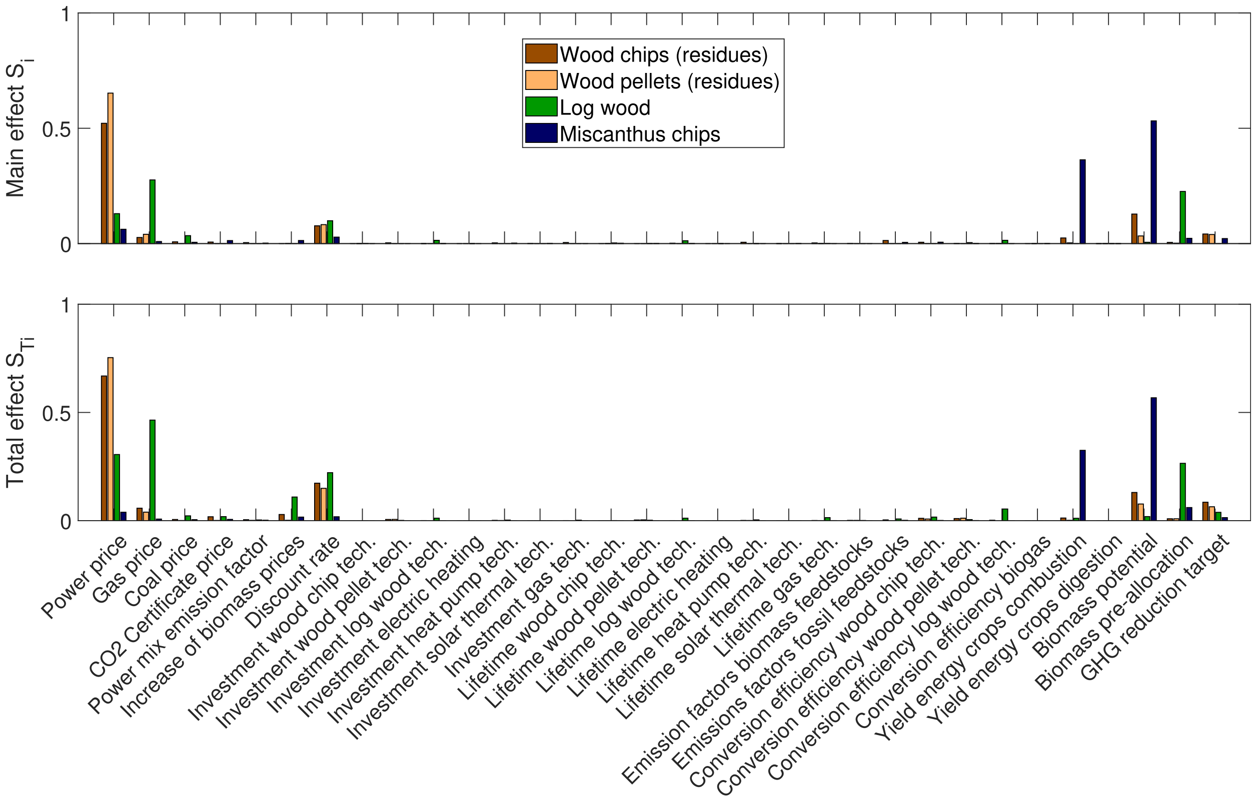

Fig. 3. Sobol' indices for the 32 investigated input parameter uncertainties on the four identified, relevant biomass products. Both Sobol' indices range from 0 to 1. $S_{Ti} \geqslant S_i \geqslant 0$. If $S_{Ti} = S_i = 0$ the parameter is non-influential. If $S_{Ti} = S_i$ there is no interaction of the i^{th} parameter with other parameters.

high log wood shares over a wide range of outcomes indicates that the use of biomass in great amounts of log wood is not a robust result. Market shares of Miscanthus chips increase with higher yields of energy crops used for combustion and lower amounts of biomass available.

3.2. Solution space

The analysis of the Sobol' indices and the scatter plots identified the uncertainty of six input parameters to be significantly influential on the market shares of four biomass products (the parameters "biomass potential" and "biomass pre-allocation" have been aggregated, as they have the same effect). This section reveals into which heat technology concepts these biomass products are distributed in. Therefore, 32 model results have been calculated with the maximum and minimum value developments of the six identified and significantly influential parameters. Figs. 7 and 8 in the appendix show which wood based technology concepts are competitive in the case of min/max parameter values. Based on the analysis of these two figures and the scatter plots, the following impacts of the six parameters on the technology market shares are identified:

- **Power and gas price**: major impact on the technology competitiveness
- **Climate target**: changes the technological competitiveness from 2040 onwards; a higher climate target increases the competitiveness of wood chip technologies
- Biomass potential/biomass pre-allocation: amplifies/weakens the technology market shares, but does not influence the choice of the technology
- High discount rate: amplifies the market share in favor of wood chip technologies and against log wood gasification systems, but does not change the technology choice
- Yield perennials: negligible influence on the competitiveness of the selected technology concepts

Evaluating sensitivity analysis, input/output scatter plots and min/max plots revealed that the choice of the cost optimal bioenergy technology concepts is found to be significantly influenced by only three out of 32 parameters: the power price, the gas price and from 2040 onwards by the climate target. Additionally two parameters have amplifying effects on the market share of the chosen technologies, the available biomass potential and the applied discount rate. Based on these results, a solution space was calculated for the possible bioenergy technology choices, considering the uncertainties of the three significantly influential input parameters.

Fig. 6 shows the calculated solution space for bioenergy technologies in the German heat sector under the min/max development curves of the future power and gas price. Within the figure, only the relevant bioenergy technology concepts are shown, leaving out fossil references, alternative renewable technologies and uncompetitive bioenergy concepts. For hybrid systems, only the solid biomass net energy shares of the concepts are displayed in order to have a comparable depiction of the biomass utilization. In cases of maximal power prices, the gas price is found not to be influential. Therefore, the climate target was also varied for maximum power prices, showing the impact of that parameter from 2040 onwards. The total net energy market share of all bioenergy technologies is in the range of $10-25\%$ from 2030 onwards. The absolute values can be seen in Figs. 6–8 (in comparison: the future net energy demand for heating is 4500 PJ in 2015 decreasing to 2700 or 3100 PJ in 2050).

The calculated solution space in Fig. 6 shows that for low power and low gas prices, the available biomass potential is almost exclusively used in the form of wood chips in high temperature industry applications. With rising gas prices, biomass is utilized in industry applications of different temperature levels. Additionally, major biomass shares are applied in log wood gasification boilers combined with solar thermal

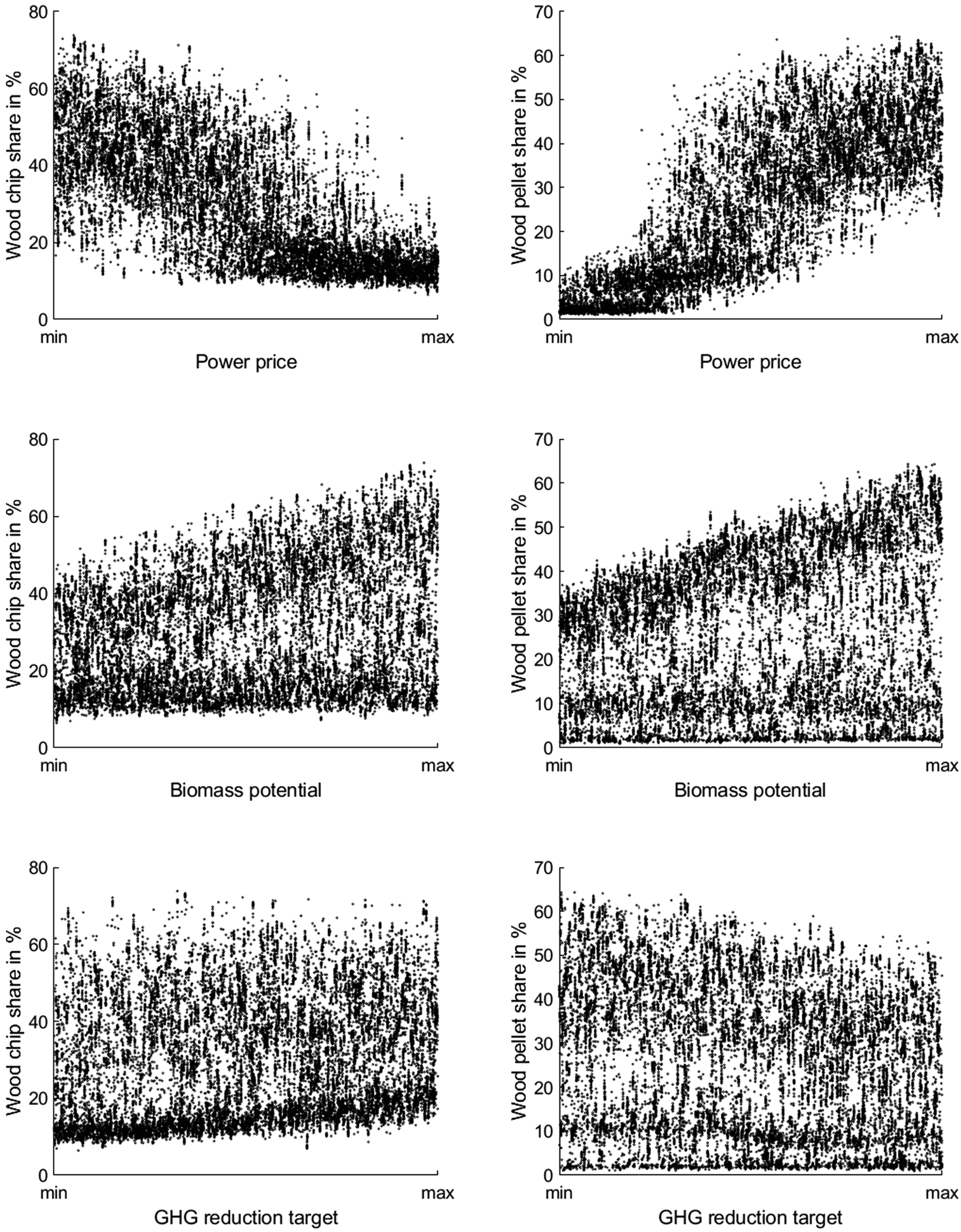

Fig. 4. Input/output scatter plots for the wood pellet (residues) and wood chip (residues) market shares, depending on the shown parameters (x-axis label). Each dot represents one of the 34000 model runs. The x-axis represents the uncertainty range of the input parameter according to Table 1.

systems in the private household sector. When power prices are high, all other parameters play a minor role on the technology choice. Hybrid systems used in the private household sector, which combine solid bioenergy technologies with heat pumps and PV, dominate the market with an additional share of wood chips in high temperature industry applications. The main hybrid system in place is a CHP (torrefied-) wood pellet combustion system. Minor biomass shares are applied to log wood gasification systems or log wood stoves in the private household sector. Towards 2050, a high climate target favors the use of biomass in high temperature industry applications, resulting in a shift

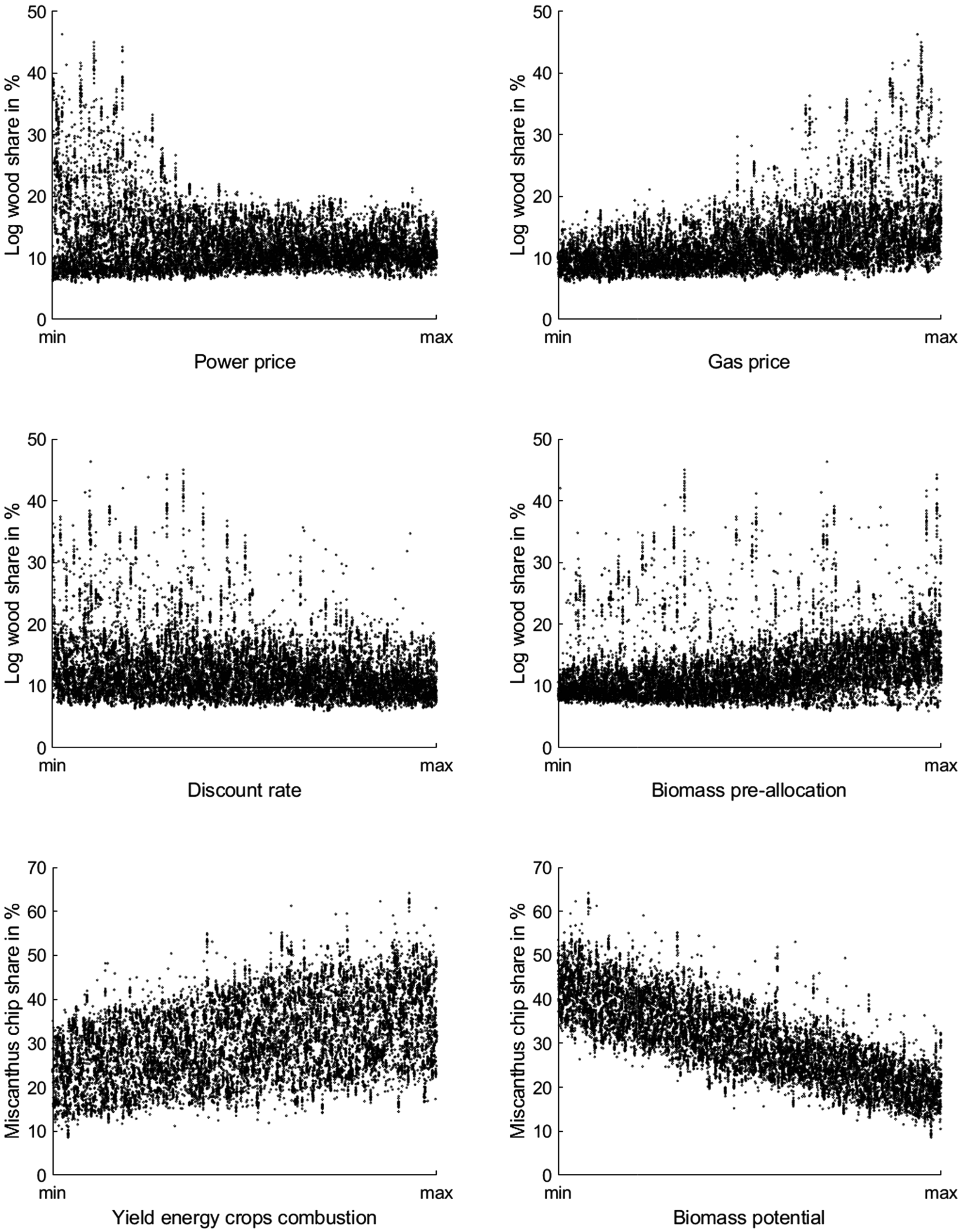

Fig. 5. Input/output scatter plots for the log wood and Miscanthus chip market shares, depending on the shown parameters (x-axis label). Each dot represents one of the 34000 model runs. The x-axis represents the uncertainty range of the input parameter according to Table 1.

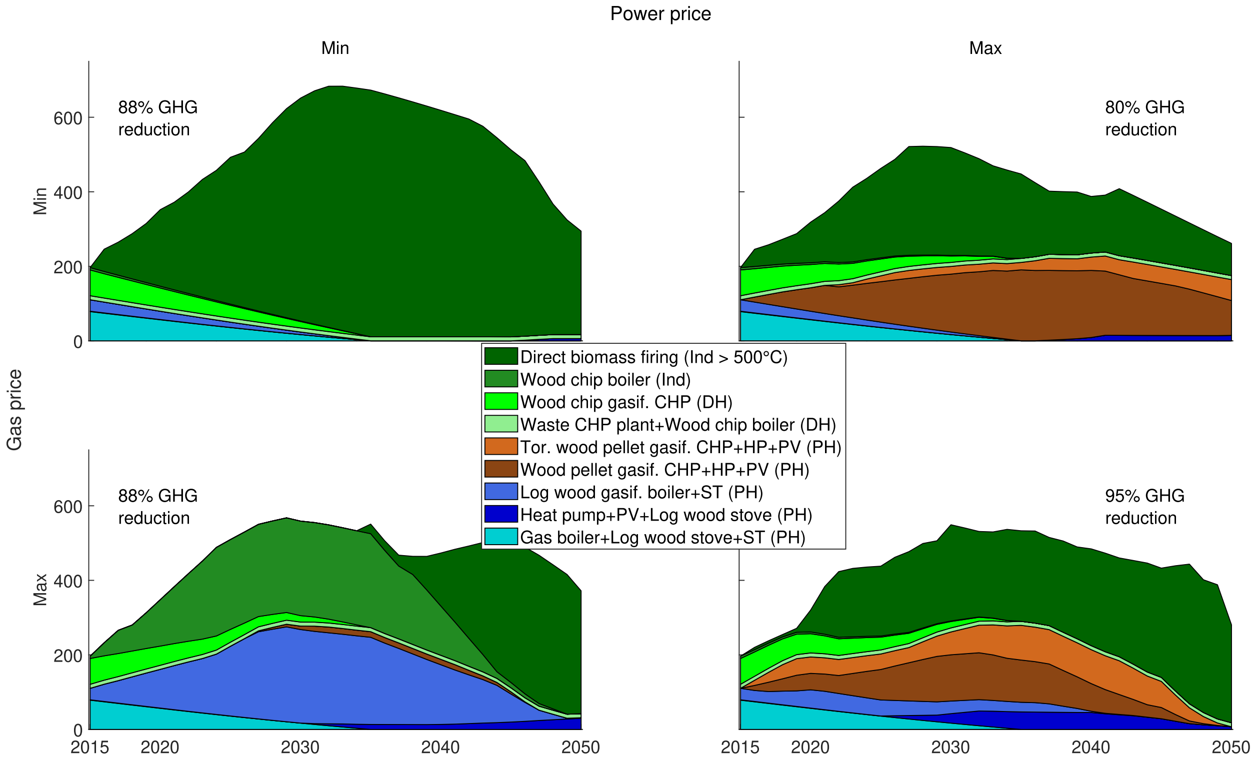

Fig. 6. Calculated solution space for the choice of bioenergy technologies, considering the defined uncertainties of the input parameters in Table 1. Displayed are the net energy market shares of the relevant bioenergy technologies in PJ. Within the figure only the relevant bioenergy technology concepts are shown, leaving out fossil references, alternative renewable technologies and unrelevant bioenergy concepts. For hybrid systems, only the solid biomass net energy shares of the concepts are displayed in order to have a depiction of the biomass utilization. All other investigated parameters, beside the "power price", "gas price" and "climate target", are set to a medium value from Table 1. Ind = Industry; DH = District Heating; PH = Private Households; CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST =. Solar Thermal.

of almost the complete available biomass away from hybrid systems into high temperature industry applications. In summary, the cost optimal allocation of the available biomass potential mainly shifts between several sub-sectors of the private household and industry sector, driven by the development of the power-, gas price and GHG reduction target.

4. Discussion

The investigation performed in this paper intends to improve the robustness of the outputs from optimization modeling and for their use in for providing policy insights. Compared to former scenario analyses [15,16], the confidence in the robustness of the model results is highly improved. Instead of the investigation of four scenarios, assessing only the min/max values of two parameters, a wide decision landscape under alternative futures was explored, covering the majority of developments with expected uncertainty, rather than all uncertainties in general. With this method, it is possible to represent the relationship between input factors and model outputs, which improves model transparency and unpacks model structure. The results confirm findings from the scenario analysis, add new findings and increase confidence in the findings.

First of all, it is found that in 99.6% of all 34000 model evaluations, climate targets could be fulfilled. This result shows that it is possible to have a successful heat transition in Germany and confirms the robustness of that statement. Of course, this is not in line with current developments in terms of meeting climate targets in the German heat sector. However, this study intends to show that, from a techno-economic point of view, it is possible to meet the climate targets in the heat sector despite all uncertain future developments. Policies or federal granting is not considered in this analysis. Second, it is found that bioenergy is a competitive option under the investigated uncertainties. In all cases, almost the complete available biomass potential, pre-allocated for heating, is used in the model. This results in total bioenergy net market shares of $10 - 25\%$ from all heating applications in Germany. Third, robust technology concepts for the future use of biomass under investigated uncertainties are identified, being significantly influenced by only a few parameters.

With the outlined method, the source of uncertainty in technology choice, could be narrowed down from 32 to only three parameters, confirming the findings from Saltelli [30] that only a few factors create almost all uncertainty, while the majority only make negligible contributions. In this study, the choice of the bioenergy technology concepts is highly influenced by the future development of the power and gas price. Additionally, the defined climate target changes the technological competitiveness from 2040 onwards. Moreover, two parameters, the available biomass potential and the discount rate, have amplifying effects, but do not influence the technology choice significantly.

The most robust technology for the future use of biomass is found to be the use of wood chips in (high temperature) industry applications. This conclusion is derived from the scatter plots of Figs. 4 and 5. A combined minimum market penetration of wood chips and Miscanthus chips of ~25% and above over a wide range of outcomes can be identified, which is a strong indication of robustness [31,4]. Additionally, the identified solution space reveals major wood chip technology market shares of $\sim 30 - 90\%$ in all cases, see Fig. 6. Finally, if a climate target towards 95% GHG reduction is aimed for, the use of wood chips from residues and energy crops in high temperature industry applications is found to be the most cost efficient way to reduce the heat based emissions in all investigated cases, see Fig. 7.

Nevertheless, with rising power prices, hybrid CHP (torrefied-) wood pellet shares increase clearly, using up to 60% of the available biomass potential. Again, the scatter plots in Fig. 4 show a high penetration of major market shares over a wide range of outcomes, which again is a strong indication of robustness. This finding confirms the results from former scenario analyses that the synergies from hybrid heat technology systems and their GHG mitigation potential are underestimated and that such systems can substantially contribute to the success of the energy transition in Germany [15,16].

A unique finding in this study is the competitiveness of log wood gasification systems, when power prices remain low and gas prices increase clearly. However, from the scatter plot in Fig. 5, a low penetration for high log wood shares can be identified, leading to the conclusion that log wood gasification systems are not a robust technology choice under future uncertainties.

Available land for energy crops is, for all model evaluations, nearly exclusively cultivated with Miscanthus, despite the large range in which the yields of Miscanthus have been varied in the sensitivity assessment (± 33%). Again, the scatter plots in Fig. 5 reveal robust market shares for Miscanthus, leading to the conclusion that the use of Miscanthus for reaching the climate targets in the German heat sector needs to be considered, despite several major barriers arising, to a large extent, from the necessary long term commitment [32]. These factors are not represented in the optimization model. A model run excluding perennial crops was performed in a former study [15], which resulted in the cultivation of maize silage for the use of biomethane in high temperature industry applications in the long term. This could be a possible business case for biomethane in the heat sector, although it was not found to be competitive in the uncertainty assessment of this investigation.

Overall, confidence in the robustness of the model results is highly improved. Additional findings could be identified and several findings from former scenario analyses can be confirmed with this study, e.g. bioenergy is not found to be competitive in the district heating and the trade and commerce sector. A robust statement about the feasibility of the German heat transition under future uncertainties is made and wood chip and pellet technologies are found to be competitive bioenergy options to fulfill the climate targets in Germany. The use of biomass in the form of wood chips in (high temperature) industry applications is found to be the most robust choice in all cases, while the hybrid CHP wood pellet systems are only robust, favorable options given increasing power prices. Additionally, when doing scenario analyses, doubts exist regarding the results, arising from the uncertainty of the model input factors. With the method applied in this paper, confidence in the robustness of the results and their use for providing policy insights is deeply improved. To the authors' knowledge, similar research, beyond simple scenario analysis, has not been performed on the future use of biomass in the German heat sector. Especially, the application of the Sobol' method in energy optimization modeling is a novel approach performed in this paper. It can serve as a case study or guideline for other researchers, who want to adapt this method and increase robustness in their ESOM results, which is highly recommended within best practice formulations for ESOMs [2]. The use of the Sobol' method identifies which parameters significantly impact the model outcome. Using scatter plots to explore these findings reveal how these parameters affect the model outcome and can focus scenario analyses. The quantification of a solution space for competitive technologies is one possibility of how to exploit these findings. A step by step description of the performed method in this paper can be found in the flow chart of Fig. 2. Theoretically, this method can be applied to any ESOM or region, the main drawback of the method is the computational cost to calculate the Sobol' indices. Therefore, the model run time has to be in the range of minutes or less. Based on the individual model run time, the number of parameters to be investigated and the number of sets required for the random value estimates need to be determined. An evaluation of the suitability of this method is recommended in each case.

4.1. Limitations

Uncertainties have become one of the major challenges of ESOMs. A wide decision landscape under alternative futures was explored in this paper. Of course, not all possible future uncertainties of the input parameters can be considered, but the majority of developments with expected uncertainty were investigated. However, it is assumed that all input parameters are independent of each other, which may not be the case. Future correlations between the parameters can occur. Nevertheless, they are hard to be expressed in numbers today and the sample size needed to compute sensitivity measures for non-independent parameters is much higher than in the case of uncorrelated samples [30].

Uncertainties referring to the imperfect mathematical relationships within the model, so called structural uncertainties, have not been investigated [3]. For example, spatial aspects of biomass availability, spatial heat demand distributions, an increased temporal resolution nor the individual investment behavior of homeowners were considered. Especially in the heat sector, with millions of homeowners, the individual behavior is potentially influential for the future market development. However, the research question investigated in this paper focuses on cost optimal solutions to fulfill the climate targets in a future German heat sector, for which the individual behavior is not considered to be imperative. However, increasing the annual resolution to an at least monthly one seems worthwhile to investigate, since the heat demand, PV yield, etc. varies seasonally.

Of course, modeling has its limits, as does this optimization model. In a future German energy system, sectors are expected to be strongly connected. Consequently, all energy sectors should ideally be modeled together and the available biomass potential could be optimally allocated over all sectors. Due to the complexity of the complete energy system, this would lead to high model run times, making it difficult to perform a systematic sensitivity analysis as done in this paper. However, with increasing shares of power based heating technologies, the heat sector is expected to be strongly connected to the power sector. Therefore, a new approach was established to link the power and heat sector without modeling the complete power sector, see Jordan et al. [15].

Additionally, the level of detail in a model is limited. The private household sector is depicted in a high level of detail, which was not possible for the industry and district heating sector due to the limited available data bases. Further research in this direction is recommended from the authors' view.

5. Conclusions

The application of the Sobol' method in energy optimization modeling is a novel approach, which can serve as a case study or guideline for other researchers. The performed method identifies parameters which impact the model outcome and how they do so. Theoretically, the method can be applied on any ESOM or region, the main drawback is the computational cost, for which the model run time has to be in the range of minutes or less.

In this paper, the applied method identified bioenergy as a robust, cost competitive option to fulfill the climate targets in a future German heat sector under a wide range of uncertain developments. The most robust use of biomass is found to be in the form of wood chips from residues and Miscanthus in (high temperature) industry applications. With rising power prices, the use of biomass in hybrid combined heat and power (torrefied-) wood pellet technologies in the private household sector is an additional robust, competitive option. Both technological concepts have the potential to close gaps in a sustainable energy system and should be considered for the future use of biomass in the German heat sector, when designing policies.

The future competitiveness of the identified, robust technology concepts is mainly influenced by the development of the power price, gas price and the defined GHG reduction target. Consequently, when designing policies, these factors should be the focus. Future shortages in the supply of renewable power need to be represented in high power prices. Additionally, solid biomass is required to be sustainably available for heating purposes and the use of Miscanthus for heating should be discussed and considered, despite the major barriers arising from the necessary long term commitment of growing perennial crops. A defined GHG reduction roadmap needs to be established, committing the industry to decarbonize its processes. When GHG reduction is mandatory for the industry sector, technologies using solid biomass as a feedstock is found to be a robust, competitive option for high temperature industry applications. The outlined recommendations are based on a comprehensive sensitivity analysis, investigating a wide range of uncertainty, and therefore provide policy insights with a high level of confidence.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Thank you to Öko-Institut e.V. for sharing the heat demand data calculated with B-STar (Building Stock Transformation Model), which have been used in this study for the defined household, trade and commerce and district heating markets [18].

Thank you to Volker Lenz and Katja Oehmichen for their expert elicitation on the defined variation of the input parameters.

Thank you to Katrina Chan for undertaking a thorough proof reading for English grammar and language.

This work was funded by the Bundesministerium für Wirtschaft und Energie (03KB113B) and the Helmholtz Association of German Research Centers and supported by Helmholtz Impulse and Networking Fund through Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE). Declarations of interest: none.

Appendix A

Figs. 7 and 8.

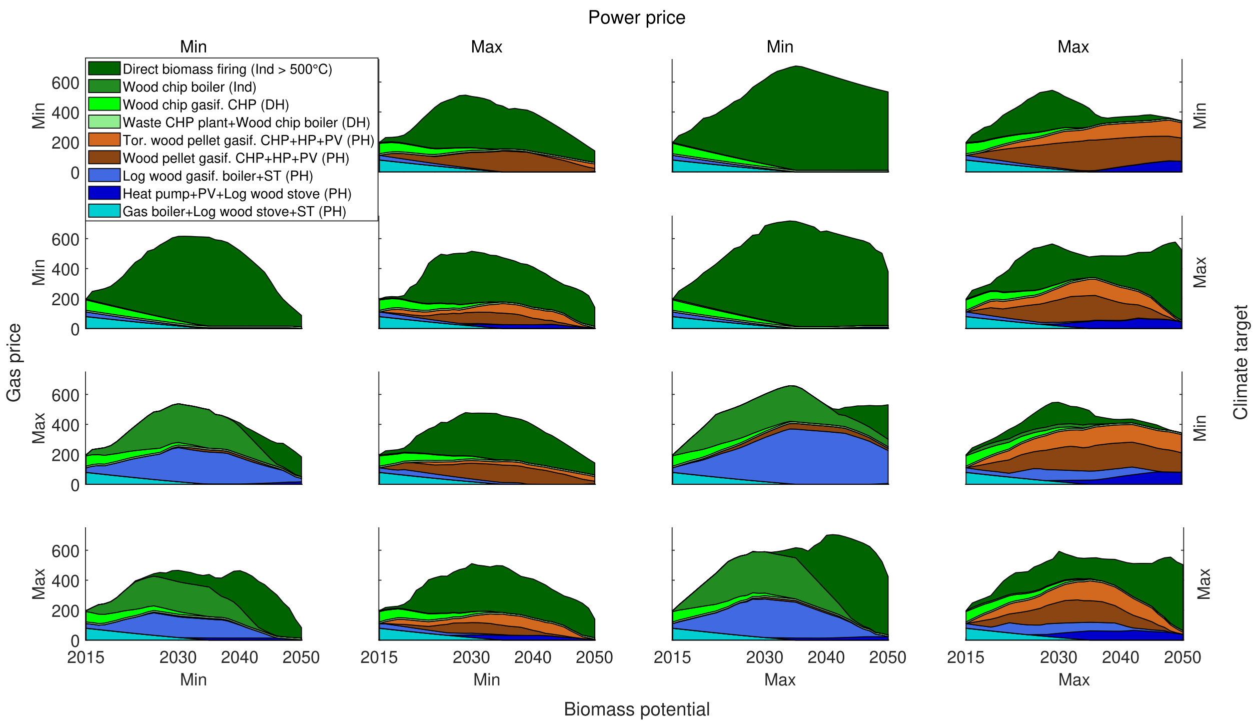

Fig. 7. Net energy market shares of the relevant solid bioenergy technologies in PJ for the min/max developments (see Table 1) of influential parameters (x-/y-labels). Ind = Industry; DH = District Heating; PH = Private Households; CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST =. Solar Thermal.

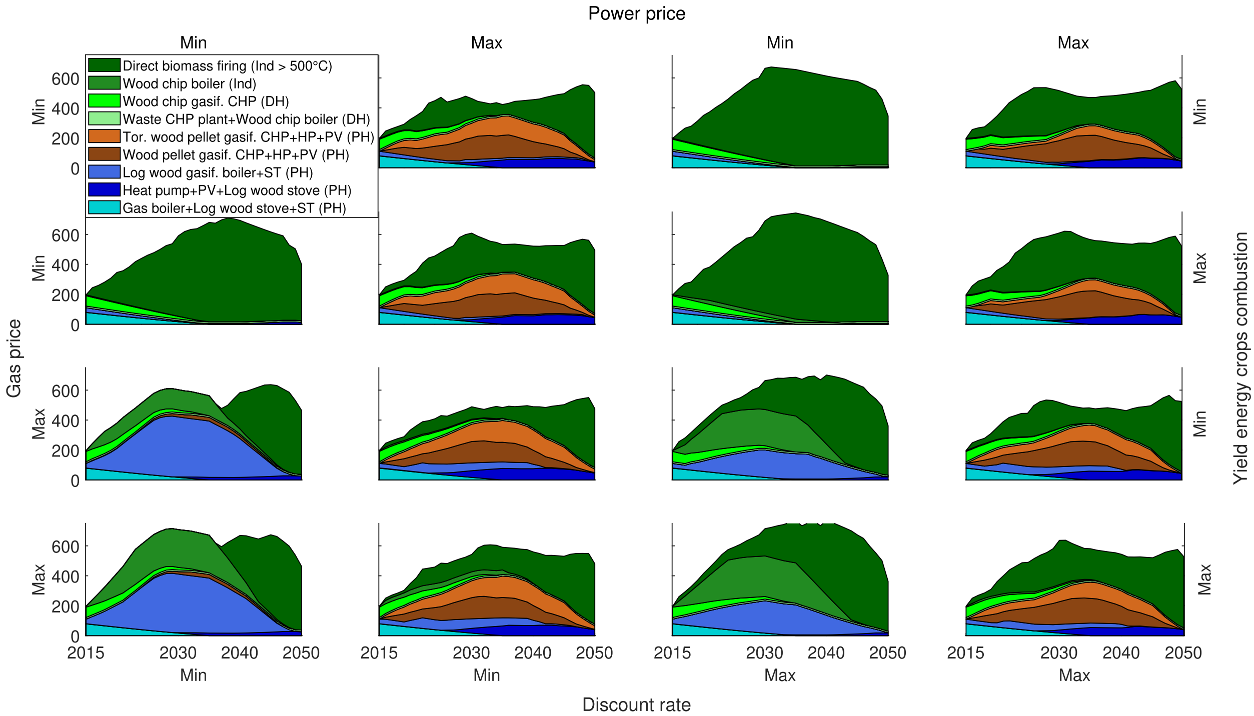

Fig. 8. Net energy market shares of the relevant solid bioenergy technologies in PJ for the min/max developments (see Table 1) of influential parameters (x-/y-labels). Ind = Industry; DH = District Heating; PH = Private Households; CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST =. Solar Thermal.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2020.114534.

References

[1] Bundesumweltamt. Erneuerbare energien in deutschland. daten zur entwicklung im jahr 2018. URL <https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/uba_hgp_eeinzahlen_2019_bf.pdf>.
[2] DeCarolis Joseph, Daly Hannah, Dodds Paul, Keppo Ilkka, Li Francis, McDowall Will, et al. Formalizing best practice for energy system optimization modelling. Appl Energy 2017;194:184–98. https://doi.org/10.1016/j.apenergy.2017.03.001.
[3] Morgan Millett Granger, Henrion Max. Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge Univ. Press, Cambridge, 1. paperback ed. edition; 1992. ISBN 9780521365420.
[4] Yue Xiufeng, Pye Steve, DeCarolis Joseph, Li Francis GN, Rogan Fionn, Gallachóir Brian Ó. A review of approaches to uncertainty assessment in energy system optimization models. Energy Strategy Rev 2018;21:204–17. https://doi.org/10.1016/j.esr.2018.06.003. ISSN 2211467X.
[5] Bosetti Valentina, Marangoni Giacomo, Borgonovo Emanuele, Anadon Laura Diaz, Barron Robert, McJeon Haewon C, et al. Sensitivity to energy technology costs: a multi-model comparison analysis. Energy Policy 2015;80:244–63. https://doi.org/10.1016/j.enpol.2014.12.012. ISSN 03014215.
[6] Usher Will, Strachan Neil. Critical mid-term uncertainties in long-term decarbonisation pathways. Energy Policy 2012;41:433–44. https://doi.org/10.1016/j.enpol.2011.11.004. ISSN 03014215.
[7] Granger Morgan M, Keith David W. Improving the way we think about projecting future energy use and emissions of carbon dioxide. Clim Change 2008;90(3):189–215. https://doi.org/10.1007/s10584-008-9458-1. ISSN 0165–0009.
[8] Moret Stefano, Gironès Víctor Codina, Bierlaire Michel, Maréchal François. Characterization of input uncertainties in strategic energy planning models. Appl Energy 2017;202:597–617. https://doi.org/10.1016/j.apenergy.2017.05.106.
[9] Mavromatidis Georgios, Orehounig Kristina, Carmeliet Jan. Uncertainty and global sensitivity analysis for the optimal design of distributed energy systems. Appl Energy 2018;214:219–38. https://doi.org/10.1016/j.apenergy.2018.01.062.
[10] Pizarro-Alonso Amalia, Ravn Hans, Münster Marie. Uncertainties towards a fossil-free system with high integration of wind energy in long-term planning. Appl Energy 2019;253. https://doi.org/10.1016/j.apenergy.2019.113528. 113528.
[11] Lythcke-Jørgensen Christoffer, Ensinas Adriano Viana, Münster Marie, Haglind Fredrik. A methodology for designing flexible multi-generation systems. Energy 2016;110:34–54. https://doi.org/10.1016/j.energy.2016.01.084. ISSN 03605442.
[12] Saltelli Andrea, Annoni Paola, Azzini Ivano, Campolongo Francesca, Ratto Marco, Tarantola Stefano. Variance based sensitivity analysis of model output. design and estimator for the total sensitivity index. Comput Phys Commun 2010;181(2):259–70. https://doi.org/10.1016/j.cpc.2009.09.018. ISSN 00104655.
[13] Yang Jian, Ma Yinjie, Jianqin Fu, Shu Jun, Liu Jingping. Parametric study of gasoline properties on combustion characteristics of gasoline compression engines using reaction kinetics simulation and density-based global sensitivity analysis. Appl Energy 2019;255. https://doi.org/10.1016/j.apenergy.2019.113858. 113858.
[14] Silva R, Pérez M, Berenguel M, Valenzuela L, Zarza E. Uncertainty and global sensitivity analysis in the design of parabolic-trough direct steam generation plants for process heat applications. Appl Energy 2014;121:233–44. https://doi.org/10.1016/j.apenergy.2014.01.095.
[15] Jordan Matthias, Lenz Volker, Millinger Markus, Oehmichen Katja, Thrän Daniela. Future competitive bioenergy technologies in the german heat sector: findings from an economic optimization approach. Energy 2019;189:116194. https://doi.org/10.1016/j.energy.2019.116194. ISSN 03605442.
[16] Jordan Matthias, Lenz Volker, Millinger Markus, Oehmichen Katja, Thrän Daniela. Competitive biomass key applications to fulfill climate targets in the german heat sector: Findings from optimization modelling. <http://www.etaflorence.it/proceedings/?detail=16385>.
[17] Saltelli Andrea. Making best use of model evaluations to compute sensitivity indices. Comput Phys Commun 2002;145(2):280–97. https://doi.org/10.1016/S0010-4655(02)00280-1. ISSN 00104655.
[18] Matthias Koch, Klaus Hennenberg, Katja Hünecke, Markus Haller, and Tilman Hesse. Rolle der bioenergie im strom- und wärmemarkt bis 2050 unter einbeziehung des zukünftigen gebäudebestandes. URL: <https://www.energetische-biomassenutzung.de/fileadmin/Steckbriefe/dokumente/03KB114_Bericht_Bio-Strom-W%C3%A4rme.pdf>.
[19] Volker Lenz and Matthias Jordan. Technical and economic data of renewable heat supply systems for different heat sub-sectors; 2019. URL https://doi.org/10.17632/v2c93n28rj.2.
[20] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Klimaschutzplan 2050 - klimaschutzpolitische grundsätze und ziele der bundesregierung: Kurzfassung. <http://www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_kurzf_bf.pdf>.
[21] Bundesregierung. Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare energieversorgung. 2010. URL <https://www.bundesregierung.de/ContentArchiv/DE/Archiv17/_Anlagen/2012/02/energiekonzept-final.pdf?__blob=publicationFile&v=5>.
[22] Dbfz - data repository: Ressourcendatenbank; 2019. <http://webapp.dbfz.de/resources>.

[23] Brosowski André, Thrän Daniela, Mantau Udo, Mahro Bernd, Erdmann Georgia, Adler Philipp, et al. A review of biomass potential and current utilisation – status quo for 93 biogenic wastes and residues in Germany. Biomass Bioenergy 2016;95:257–72. https://doi.org/10.1016/j.biombioe.2016.10.017. ISSN 09619534.
[24] Lwf merkblatt: Der energieinhalt von holz, 26.06.2019. <http://www.lwf.bayern.de/mam/cms04/service/dateien/mb-12-energiegehalt-holz.pdf>.
[25] Energiegehalt von hackschnitzeln: Überblick und anleitung zur bestimmung, 25.06.2019. <https://www.waldwissen.net/waldwirtschaft/holz/energie/fva_energiegehalt_hackschnitzel/fva_energiegehalt_hackschnitzel.pdf>.
[26] Doering Przemko, Glasenapp Sebastian, Mantau Udo. Energieverwendung in privaten haushalten. Abschlussbericht: Marktvolumen und verwendete holzsortimente; 2014.
[27] Szarka Nora, Eichhorn Marcus, Kittler Ronny, Bezama Alberto, Thrän Daniela. Interpreting long-term energy scenarios and the role of bioenergy in Germany. Renew Sustain Energy Rev 2017;68:1222–33. https://doi.org/10.1016/j.rser.2016.02.016. ISSN 13640321.
[28] Cuntz Matthias, Mai Juliane, Zink Matthias, Thober Stephan, Kumar Rohini, Schäfer David, et al. Computationally inexpensive identification of noninformative model parameters by sequential screening. Water Resour Res 2015;51(8):6417–41. https://doi.org/10.1002/2015WR016907. ISSN 00431397.
[29] McKay MD, Beckman RJ, Conover WJ. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 1979;21(2):239–45. https://doi.org/10.1080/00401706.1979.10489755. ISSN 0040–1706.
[30] Saltelli A. Global sensitivity analysis: the primer. Chichester England and Hoboken NJ: John Wiley0470059974; 2008.
[31] Heaton Chris. Modelling low-carbon energy system designs with the eti esme model. Energy Technologies Institute; 2014. URL <https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2014/04/ESME_Modelling_Paper.pdf>.
[32] Witzel Carl-Philipp, Finger Robert. Economic evaluation of miscanthus production – a review. Renew Sustain Energy Rev 2016;53:681–96. https://doi.org/10.1016/j.rser.2015.08.063. ISSN 13640321.
[33] Repenning Julia, Emele Lukas, Blanck Ruth, Böttcher Hannes, Dehoust Günter, Förster Hannah, et al.. Klimaschutzszenario 2050: 2. endbericht -studie im auftrag des bundesministeriums für umwelt, naturschutz, bau und reaktorsicherheit. <https://www.oeko.de/oekodoc/2451/2015-608-de.pdf>.
[34] Schlesinger Michael, Lindenberger Dietmar, Lutz Christian. Entwicklung der energiemärkte - energiereferenzprognose: Projekt nr. 57/12 studie im auftrag des bundesministeriums für wirtschaft und technologie. <https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht.pdf?_blob=publicationFile&v=7>.
[35] Strommarktstudie 2030: Ein neuer ausblick für die energiewirtschaft. <https://www2.deloitte.com/content/dam/Deloitte/de/Documents/energy-resources/Deloitte-Strommarktstudie-2030.pdf>.
[36] Energy brainblog, 2019. https://blog.energybrainpool.com/update-trends-der-strompreisentwicklung-eu-energy-outlook-2050/.
[37] Eu reference scenario: Energy, transport and ghg emissions trends to 2050, c. <https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf>.
[38] World energy outlook; 2018.
[39] Strommarkt 2050: Analyse möglicher szenarien der entwicklung des deutschen und mitteleuropäischen strommarktes bis zum jahr 2050. <https://get.fh-erfurt.de/fileadmin/GET/Dokumente/Download/Forschung-Lenz/Studie_Strommarkt_2050.pdf>.
[40] Pfluger Benjamin, Tersteegen Bernd, Franke Bernd. Langfristszenarien für die transformation des energiesystems in deutschland: Modul 3: Referenzszenario und basisszenario studie im auftrag des bundesministeriums für wirtschaft und energie, a. <https://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-3-referenzszenario-und-basisszenario.pdf?_blob=publicationFile&v=4>.
[41] Nitsch Joachim, Pregger Thomas, Naegler Tobias, Heide Dominik, de Tena Diego Luca, Trieb Franz, et al. Langfristszenarien und strategien für den ausbau der erneuerbaren energien in deutschland bei berücksichtigung der entwicklung in europa und global: Schlussbericht. <http://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf>.
[42] Eu energy, transport and ghg emissions - trends to 2050: Reference scenario 2013, b. <https://ec.europa.eu/transport/sites/transport/files/media/publications/doc/trends-to-2050-update-2013.pdf>.
[43] Options for gas supply diversification for the eu and germany in the next two decades. <https://www.ewi.research-scenarios.de/cms/wp-content/uploads/2016/10/Options-for-Gas-Supply-Diversification.pdf>.
[44] Energy transition outlook 2018: A global and regional forecast to 2050.
[45] Energy roadmap 2050, a. <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy>.
[46] Pfluger Benjamin, Tersteegen Bernd, Franke Bernd. Langfristszenarien für die transformation des energiesystems in deutschland: Modul 1: Hintergrund, szenarioarchitektur und übergeordnete rahmenparameter studie im auftrag des bundesministeriums für wirtschaft und energie, b. <https://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-1-hintergrund-szenarioarchitektur-und-uebergeordnete-rahmenparameter.pdf?_blob=publicationFile&v=4>.
[47] Nitsch Joachim. Szen-15: Aktuelle szenarien der deutschen energieversorgung unter berücksichtigung der eckdaten des jahres 2014. URL <https://www.bee-ev.de/fileadmin/Publikationen/20150419-Szenarien_SZEN-15.pdf>.
[48] Modell deutschland: Klimaschutz bis 2050. <https://mobil.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/WWF_Modell_Deutschland_Endbericht.pdf>.
[49] Steinbach Jan, Staniaszek Dan. Discount rates in energy system analysis: Discussion paper; 2015. URL <http://bpie.eu/uploads/lib/document/attachment/142/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf>.
[50] Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL). Energiepflanzen. Daten für die Planung des Energiepflanzenanbaus. (KTBL) 2012.

Paper 3

Incorporating consumer choice into an optimization model for the German heat sector: Effects on projected bioenergy use.

Jordan, M., Hopfe, C., Millinger, M., Rode, J. and Thrän, D.

Journal of Cleaner Production (2021)

Journal of Cleaner Production 295 (2021) 126319

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Incorporating consumer choice into an optimization model for the German heat sector: Effects on projected bioenergy use

Matthias Jordan [a, c, *], Charlotte Hopfe [d], Markus Millinger [a], Julian Rode [a], Daniela Thrän [a, b, c]

[a] Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318, Leipzig, Germany
[b] DBFZ Deutsches Biomasseforschungszentrum GGmbH, Torgauer Strasse 116, 04347, Leipzig, Germany
[c] University Leipzig, Institute for Infrastructure and Resources Management, Grimmaische Str. 12, 04109, Leipzig, Germany
[d] University Bayreuth, Department of Biomaterials, Prof.-Rüdiger-Bormann-Str. 1, Bayreuth, Germany

A R T I C L E I N F O

Article history:
Received 21 August 2020
Received in revised form
5 February 2021
Accepted 6 February 2021
Available online 19 February 2021

Handling editor: Dr Sandra Caeiro

Keywords:
Heat sector
Bioenergy
Optimization
Consumer choice
Investment behavior

A B S T R A C T

The energy transition requires policy makers to adopt a holistic view that also considers non-economic factors when developing cleaner technology deployment schemes. In particular, a broad knowledge base is required to ensure an efficient energetic use of the limited biomass potential. Energy system optimization models are widely used to inform decision makers about energy transition strategies. The heterogeneity of consumers, especially in the heat sector, is rarely considered in these models and therefore these models lack of completion to contribute to this holistic approach. In this study, a literature review was conducted to find empirical data on consumer behavior regarding the adoption of residential heating systems. This data was integrated into an optimization model for the German heat sector, combining established methods for integrating consumer heterogeneity with a novel approach for calculating indirect costs representing behavioral factors. The incorporation of consumer choice leads to a broader distribution of market shares of different technologies in both a “business-as-usual” scenario and an “ambitious measures” scenario. In particular, the future role of log wood technologies in the private household sector may have been underestimated in previous studies and should be discussed, when designing policies. With this study, the knowledge base for decision makers was extended to discuss the future efficient use of biomass within the German heat sector.

1. Introduction

Germany has set itself the target of reducing GHG emissions by 80–95% by 2050 compared to 1990, including emissions from the heat sector, which are responsible for 53.5% of German energy demand (Bundesministerium für Wirtschaft und Energie, 2019). The heat sector is characterized by its heterogeneity – not only from a technical point of view. In addition to varying heat demand profiles, applications and infrastructures, the sector has a wide variety of stakeholders with different interests and consumer behaviors. For instance, millions of homeowners in the private household sector, which account for 43% of German heat demand (Bundesministerium für Wirtschaft und Energie, 2019), choose a heating system based on their own investment decisions. Thus, future market development is not influenced by economically rational behavior alone: as is well known, private investment and consumption decisions can be influenced by many factors that deviate from the assumption of economic rationality (DiClemente and Hantula, 2003; Kahneman and Tversky, 1984). Energy system optimization models (ESOMs) are widely used to inform about energy transition strategies. Investment behavior that does not conform to standard economic rationality may influence projected market developments in the future and poses a methodological challenge to ESOMs, which rely on the assumption of cost minimization.

In the German heat sector in 2019, 14.5% of heat demand was supplied by renewable energy sources (Umweltbundesamt, 2020). Of more than 32 million heating systems installed (Bundesverband des Schornsteinfegerhandwerks, 2018), ~ 12 million are bioenergy heating systems (Bundesverband des Schornsteinfegerhandwerks, 2018; Rönsch, 2019), constituting the major share of renewable

* Corresponding author. Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318, Leipzig, Germany.
E-mail address: matthias.jordan@ufz.de (M. Jordan).

https://doi.org/10.1016/j.jclepro.2021.126319

heat. Today as well as in the future a variety of bioenergy strategies are expected to provide renewable heat (Jordan et al., 2019) also in a flexible way (Lenz et al., 2015). Bioenergy users are influenced, among other things, by the local availability of log wood, for instance through forest ownership. Consequently, projections produced by ESOMs are limited and might be too optimistic or misleading when relying on cost minimization alone. In order to inform policy in a more robust way, purely cost-based analyses need to be complemented by methods that include consumer heterogeneity and the behavioral factors other than cost minimization that influence investment decisions.

There is a need to combine insights from different energy transition disciplines, such as those concerned with economic development, policy change and consumer behavior (Cherp et al., 2018). However, consumer choice is often poorly represented in such models, with hurdle rates, market share constraints or technology growth rates, among other factors, being used to smooth out projections (DeCarolis et al., 2017). Instead, modeling methods are required that are based on robust theoretical underpinnings and conclusive empirical observations.

Methodological progress has been made in recent years, especially for ESOM projections in the transport sector. The most common approach, identified in reviews by DeCarolis et al. (DeCarolis et al., 2017) and Venturini et al. (2018), is to create different consumer segments to represent the heterogeneity in consumer choice (Bunch et al., 2015; Cayla and Maïzi, 2015; Daly et al., 2014; Li and Strachan, 2019; Li et al., 2018; McCollum et al., 2017; Ramea et al., 2018; Tattini et al., 2018). A bottom-up model structure with a high level of detail has been found to be most promising for this purpose (Venturini et al., 2018). Different approaches exist to incorporate more realistic consumer choice within the consumer segments. Some optimization models are linked with a nested nomial logit model (MNL) (Horne et al., 2005). The basic aim of multinomial logistic regression is to calculate the probability of a certain event occurring by matching data to a logistic curve (Backhaus et al., 2016). Another approach is to introduce indirect costs such as disutility costs, willingness to pay, or the quantification of modal preferences via the monetization of intangible costs (Tattini et al., 2018) for the different technology concepts. McCollum et al. (2014) first introduced disutility costs, which make it possible to consider (non-monetary) discomfort costs. This approach has been applied fairly extensively in different model frameworks (Bunch et al., 2015; McCollum et al., 2017; Ramea et al., 2018).

For the heat sector, little progress has been made so far in incorporating consumer choice into ESOMs, despite the heterogeneity of consumers. Cayla and Maïzi (2015), Cayla and Osso (2013) conducted a survey and identified three key parameters influencing consumer choice in the French heat sector. Based on these parameters, a segmentation in the TIMES model was conducted. 38 also applies consumer segmentation for the heat sector in the UK TIMES model to represent technology investment behavior. Actual technology adoption behavior is then based purely on survey results, excluding economic factors. In literature, the relevance of behavioral factors that influence investment decisions is found to vary considerably between countries (Li et al., 2018). Depending on the country on which the study is performed, the methodological approaches for calculating indirect costs vary depending on the country specific influencing factors. A simple transfer of the methods from e.g. the French region to the German case is therefore not applicable.

In the literature, an understanding exists that economic and non-economic determinants need to be considered whenever technology deployment schemes are developed (Cherp et al., 2018; Kennedy and Basu, 2013; Kennedy et al., 2016). Policy makers need to adopt a holistic view in order to understand how to encourage heat consumers to adopt cleaner heating systems (Su et al., 2019; VainioAnna et al., 2020). In the case of Germany, there is a lack of research addressing this issue. Empirical data on consumer behavior related to heating systems is available (Michelsen and Madlener, 2013), but its influence on heat transition scenarios has not yet been assessed in ESOMs. The goal of the present study is to provide a broader basis for designing a cleaner system of heat production in housing and industry applications.

For this purpose, a literature review was conducted to identify the behavioral factors, other than cost minimization, that influence investment decisions in relation to consumer heating systems. The empirical data gathered from this review was integrated into an optimization model for the German heat sector using methods derived from recent studies. The concept of consumer segmentation, in which different indirect costs are introduced, is applied. Factors influencing actual heating behavior after the installation of the system are not considered in this study.

The optimization model used in this study was developed to determine the optimal use of bioenergy in the German heat sector in different scenarios and given future uncertainties (ETA-Florence Renewable Energies, 2019; Jordan et al., 2019; Jordan et al., 2020). In this study, the model is extended to include consideration of households' investment behavior in relation to different heating technologies, the aim being to produce more credible projections or policy insights and to address the following research question: Which model projections arise in the German heat sector under consideration of consumer choice in different scenarios?

2. Materials and methods

2.1. Behavioral factors influencing the adoption of residential heating systems: A literature review

In order to find empirical data on consumer behavior that can be incorporated into an ESOM, we proceeded in three steps: first, we conducted a literature review to identify behavioral factors that influence consumer investment decisions around heating systems in Germany. Second, we searched the literature for empirical data to understand the relevance and strength of influence of the different factors. Third, we selected data and a typology of consumer segments that was compatible with the requirements of the model.

The literature review was conducted in two phases. First, two publications that were randomly selected from the relevant literature (Michelsen and Madlener, 2012; Steinbach, 2015) and the literature cited within them ($n = 75$) were analyzed to extract relevant keywords. Second, following the recommendations for literature reviews by Khan et al. (2003), a search strategy was specified that contained inclusion and exclusion criteria. The Google Scholar and Web of Science databases were searched using a combination of the keywords thus identified, as shown in Fig. 1. All the terms under A) were combined with B) and all terms of C); similarly, all keywords in boxes D) and E) were combined with one another. The search was conducted in both English and German. Relevant literature was identified by title and abstract, resulting in 135 publications of interest. Articles were included in the review and analyzed in more detail if they contained surveys (both quantitative and qualitative), causal analysis, discrete choice models, cluster analysis or literature reviews based on data collected in Germany. Studies based on social demography, surveys related exclusively to system refurbishment, with hypothetical selection options, or a sole focus on heating behavior were excluded. This resulted in 16 publications that were relevant for assessing influences on consumers— heating system choices in Germany.

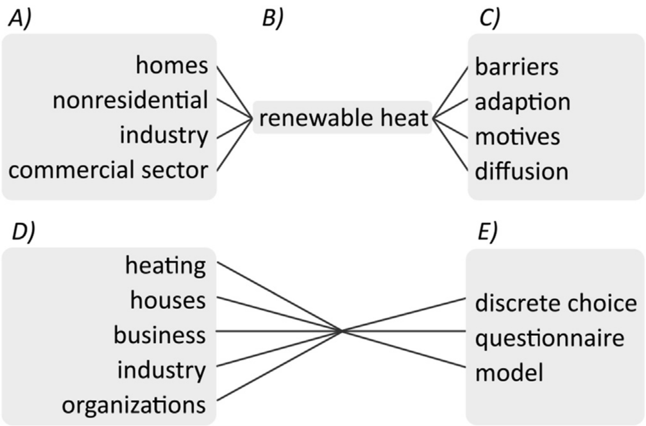

Fig. 1. Keywords used in literature search. Keywords under A) were combined with B) and C); all keywords of D) and E) were combined with each other.

One finding of this literature review is that empirical data on consumer choice regarding heating systems is available only for single- and two-family houses. No empirical data on consumer heating system choice could be found for multi-family houses, the trade and commerce sector or industrial facilities.

The 16 studies thus identified were reviewed in more detail and the factors influencing consumer choice in relation to heating systems were analyzed qualitatively and grouped into three categories, see Table 1. Alongside financial motives, which all the studies found to be influential, non-financial motives such as the comfort in operating and preferences on eco-friendliness of the heating system were most often found to influence consumer choice. Factors related to heuristic/imperfect information processing, were also found in various studies.

The principal goal of this literature review was to find empirical data on consumer choice capable of being incorporated into an optimization model for the German heat sector and simultaneously reflecting the picture found in the literature review. As the refurbishment of building stock is an external input and not determined within the model, only data on the choice of heating system is relevant for the optimization model. Additionally, the model deals solely with data on fossil fuel, bioenergy and alternative renewable technologies so that studies related exclusively to solar photovoltaics (Klein and Deissenroth, 2017; Korcaj et al., 2015), studies focusing on only one type of heating technology (Braun, 2010; Mills and Schleich, 2009; Woersdorfer and Kaus, 2011) and review studies (Gossen and Nischan, 2014) were excluded. As a result, three survey-based empirical data sets were found to be potentially suitable for incorporation into the optimization model. These are described here in more detail.

Stieβ et al. (Stieß et al., 2010) surveyed 1009 homeowners in 2008 on the factors influencing their heating refurbishment decision and analyzed the data generated (Stieβ and Dunkelberg, 2013; Zundel and Stieβ, 2011). In this survey, the choice of heating system is included in the refurbishment decision. Additionally, not all required heating systems are differentiated within this study. Consequently, this data set was not considered to be incorporated into the optimization model.

Decker et al. (2009) surveyed 775 homeowners in 2007 regarding their motivation for adopting a residential heating system. A factor analysis and cluster analysis were performed on the data collected using a multinomial logistic regression model (MNL) (Decker and Menrad, 2015; Decker et al., 2009; Decker, 2010). One of the main findings is that membership in different “ecological clusters” is the main influencing factor on the choice of a certain heating system. An ecological cluster is defined as the general attitude of a consumer towards environmental conservation. However, compared to other studies dealing with the purchase of a certain heating system, the survey response rate was fairly low (Decker and Menrad, 2015).

The empirical basis for the studies conducted by Michelsen and Madlener, 2012, 2013, 2016, 2017 is a questionnaire survey (N = 2440) conducted in 2010 among homeowners who had recently installed a residential heating system. An MNL model was applied to the data by Michelsen and Madlener (2013). This made it possible to identify the motivational factors influencing homeowners’ decisions about adopting a residential heating system (RHS). Additionally, a characterization of the motivational factors was conducted using a principal component analysis, the participants of the survey being grouped into three clusters using a cluster analysis: the convenience-oriented (C1), the consequences-aware (C2), and the multilaterally-motivated (C3) RHS adopter, see Table 2. The clusters cover 25 influencing factors, which were grouped around six components by Michelsen and Madlener (2013). The probability of belonging to one of the three clusters

Table 1
Influential factors on the heating technology consumer choice identified in literature. The number of studies indicates in how many studies a statistical significant influence was identified. Factors marked in italic are not represented in the chosen data set from Michelsen and Madlener (2013), which is used in this study.

Category	Motivational factors	Influence in the direction of	Study numbers
financial motives	Costs (investment/annual costs/maintenance/fuel)		16
	Technological efficiency		1
	Financial support	Renewable heating	5
	Influence on value of the house	Renewable heating	3
	Risk aversion/preference for certainty		2
	Preference for short amortization period	Gas/Oil	2
	Aversion against debt/taking credit		1
non-financial motives	Comfort in operating/“climate” of living	Gas/Heat pump	9
	Preference for eco-friendliness (energy saving)	Renewable heating	8
	Preference for modern/progressive technology	Renewable heating	4
	Preference for independence from fossil fuels/autarky	Renewable heating	3
	aesthetics (appearance of the house)		3
	Prestige/social status	Renewable heating	3
	Concern for quality (e.g. fear of construction damage)		2
	Attitudes regarding/evaluation of fuel type		1
heuristic/imperfect information processing	Incomplete/imperfect knowledge via different channels		6
	Laziness, indifference (avoiding a complicated process)	Gas/Oil	3
	Imitation (e.g. neighbors)		3

Table 2
Identified clusters by Michelsen and Madlener (2013): The convenience-oriented (C1) RHS adopter is mainly motivated by comfort considerations and the general attitude towards the RHS. The heating system should fit well into his daily routines. The consequences-aware (C2) RHS adopter considers financial benefits, rising energy prices, supply security (e.g. independence of fossil fuels) and environmental reasons. The multilaterally-motivated (C3) RHS adopters strongly engage in the decision, based on a variety of aspects (in particular cost aspects, grants, comfort considerations and influence of peers). In addition, the MNL analysis results for predicting the probability of belonging to one of the three clusters (cluster membership) are presented as average marginal effect (M.E.) (Michelsen and Madlener, 2013).

	C1	C2	C3
Consumer share	54.4%	32.2%	13.4%
Gas + solar termal	0.064	−0.096	0.033
Heat pump	−0.132	0.026	0.105
Wood pellet	−0.398	0.330	0.068

was predicted by means of a MNL model (Michelsen and Madlener, 2013) that considers the interaction between all 25 influencing factors affecting the consumers choice of heating technology, see also Table 2. The factors identified reflect all those identified in the literature except four, as summarized in Table 1.

The empirical data presented by Michelsen and Madlener (2013) are analyzed by them in detail, their study is one of the most recent ones available with a high number of participants, and their findings are largely in line with the general findings of the literature review and the findings of Decker and Menrad (2015). Consequently, the results of Michelsen and Madlener (2013) were selected in this study for incorporation into the optimization model to represent consumer choice.

2.2. The optimization model

The optimization model has been used in previous research to determine the future cost optimal use of biomass in the German heat sector in different long term climate mitigation scenarios (ETA-Florence Renewable Energies, 2019; Jordan et al., 2019; Jordan et al., 2020). In the present study, the structure of the model and the data have been extended to depict consumer investment behavior, see section 2.3. Apart from this extension and not setting an upper limit for greenhouse gas emissions, the same model formulations are applied as in Jordan et al. 26. In this study, the model is used to project future market development assuming that all the actors behave in an economically rational way, except for the behavioral aspects that are integrated into the model. This includes that all actors have perfect foresight and consumers are aware of future price and demand developments.

The approach of the model follows the BENOPT (Bio-ENergyOPTimisation) model developed for biofuels assessment in the transport sector (Millinger et al., 2018, 2019; Millinger, 2019). The model is structured as follows: the three main sectors of the German heat sector – private household, industry and trade/commerce – are further divided into several sub-sectors, each with different properties in terms of demand profiles and infrastructures. In total, 19 sub-sectors are defined and described: five sub-sectors for single-family houses (SFH), four for multi-family houses, five for the trade and commerce sector and five for industry and district heating. The future development of heat demand in buildings is based on the results of the building stock model 'B-STar' (Koch et al., 2018), which models the future refurbishment of German building stock at a yearly resolution using an agent based approach. As a result, consumers' decisions regarding refurbishment cannot be represented in this model. Within the optimization model, representative bioenergy, fossil and other renewable (hybrid) heat technology concepts are described for each sub-sector (Lenz and Jordan, 2019), including, e.g. gas boilers, heat pumps, direct electric heating, solar thermal, log wood, wood pellet and wood chip technologies. In total, 23 biomass products (including wood based residues, log wood, straw, manure, two perennial crops and seven types of energy crops) and three fossil feedstocks are possible inputs (Lenz and Jordan, 2019). For the single technology components, infrastructure emissions as well as the feedstock specific emissions are considered within the model.

The various components of the power price (e.g. taxes and levies) are treated separately in the model and their future development is set according to projected trends (Consentec GmbH and Fraunhofer, 2018; Götz et al., 2013; Haller et al., 2015). This leads to different power prices in the heat sub-sectors (private households, trade/commerce and industry), despite applying the same projection for the stock market power price. A detailed description of the method and the time series applied are attached in the supplementary material.

Choice of technology is optimized between 2015 and 2050 at a yearly resolution. The objective function minimizes the total system costs across all technologies, sub-sectors and the full time span, using the Cplex solver for the linear optimization problem. The spatial boundary is Germany as a whole and the sectoral coverage exclusively encompasses the heating sector. For a detailed description of the model formulations, the linkage to the power sector, the definition of the sub-sectors and technology concepts, as well as the possible feedstock and technology pathways, the reader is referred to Jordan et al. (2019). Detailed economic and technical data for the technology concepts can be found in a data publication (Lenz and Jordan, 2019).

2.3. Integrating consumer behavior into the optimization model

The integration of consumer choice into the model depicting the adoption of residential heating systems is based on the studies conducted by Michelsen and Madlener, 2012, 2013, 2016, 2017. Specifically, the results from the cluster analysis and from the analysis predicting cluster membership are used in this study (Michelsen and Madlener, 2013), see Table 2. The cluster segmentation is the basis for splitting the relevant heating sub-sectors into consumer segments, the same approach as in Li et al. (2018). In this case, the heat demand of all five single-family sub-sectors, responsible for $\sim 23\%$ of German heat demand, were further segmented into three consumer segments (C1..C3) each, representing the clusters identified from Michelsen and Madlener (2013). A schematic representation of how the consumer segmentation and the application of indirect costs is realized in the model is shown in Fig. 2.

As shown in section 2.1 while the adoption of a heating system is driven largely by financial motives, non-financial ones are also relevant (mainly in terms of comfort and environmental concerns, see Table 1). The financial aspects are represented comprehensively in the optimization model (investment, fixed and variable costs). The non-financial motives are represented via indirect technology costs. In each consumer segment, different indirect costs are applied, following established approaches in the literature (Bunch et al., 2015; McCollum et al., 2014; McCollum et al., 2017; Ramea et al., 2018; Tattini et al., 2018). In this case, the indirect costs are derived from predicting which heating systems belong to which one of the three clusters, see Table 2, presented as average marginal effect (M.E.). This marginal effect is translated into indirect costs derived from an economic textbook approach: according to economic theory, market shares of two technologies sh_1 and sh_2 should be inversely related to their relative cost c_1/c_2 (Zweifel et al., 2017),

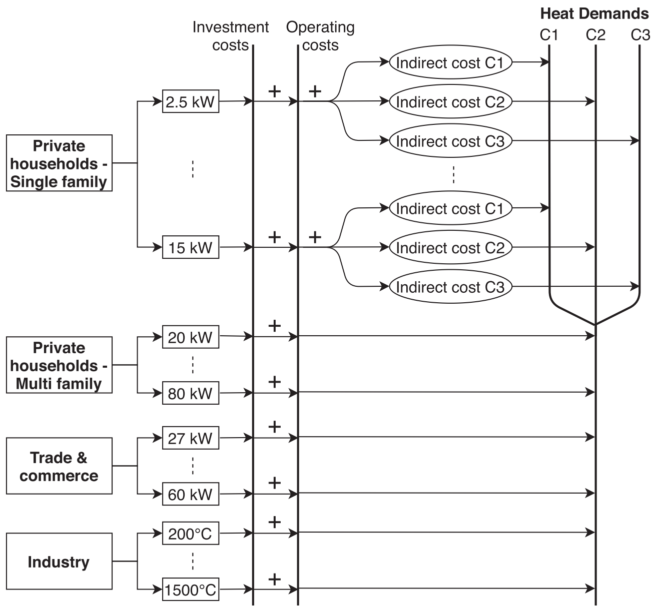

Fig. 2. Schematic of applying indirect costs in the different consumer segments C1..C3 within the optimization model. The sub-sectors are defined by the size of the heating system, e.g. 2.5 kW.

with the parameter g indicating the extent to which cost differentials between competing technologies affect their market shares.

$$\frac{sh_1}{sh_2} = \left(\frac{c_2}{c_1}\right)^g \; with \; g > 0 \tag{1}$$

As a conclusion derived from this causality, an increased probability of technology market shares (probability of cluster membership, see Michelsen and Madlener 42) is translated into a decrease in costs and vice-versa. Since market shares in the optimization model are based on costs alone, represented by the objective function, here we translate the probability of cluster membership directly into an indirect cost factor *icf* for each

Table 3
Indirect cost factor (icf) derived from the M.E., see Table 2 for the relevant technology concepts in the different consumer segments (C1..C3). As there is no differentiation between adopting a wood pellet or log wood technology, the M.E. for log wood technologies is set equal to the one of wood pellets. For hybrid systems the indirect cost factor is calculated from an equal average of the applicable M.E. PV systems are not explicitly considered.

	C1	C2	C3
Heat demand share	54.4%	32.2%	13.4%
Gas cond. boiler	0.064	−0.096	0.033
Gas boiler + Log wood stove + ST	−0.167	0.117	0.0505
Gas cond. boiler + ST	0.064	−0.096	0.033
Gas fuel cell + ST	0.064	−0.096	0.033
Heat pump + PV	−0.132	0.026	0.105
Heat pump + PV + ST	−0.132	0.026	0.105
Heat pump + PV+ Log wood stove	−0.265	0.178	0.0865
Pellet boiler	−0.398	0.33	0.068
Buffer integrated pellet burner + ST	−0.398	0.33	0.068
Log wood gasif. boiler + ST	−0.398	0.33	0.068
Log wood stove + ST	−0.398	0.33	0.068
Torrefied wood pellet gasifier CHP	−0.398	0.33	0.068
Tor. wood pellet gasif. CHP + HP + PV	−0.265	0.178	0.0865

applicable technology system within the consumer segments, see Table 3. In an ideal case, the indirect costs factor would be calibrated with the parameter g, which was not possible in this study. The indirect cost factor is incorporated into the objective function by adding the inverted indirect technology costs proportional to the investment costs *ic* and variable costs *mc* of each technology *i*, see equation (2). With this method, negative indirect costs can also apply, representing a willingness to pay. The investment costs are discounted using the annuity method (discount rate q, lifetime $\widehat{t}$). Finally, the objective function minimizes the total system costs over all technology modules j, all sub-sectors s, feedstock products b and the complete timespan $t = 2015...2050$.

Objective function

$$\begin{aligned} min \sum_{t,i,s,b} & mc_{t,i,s,b} \cdot \pi_{t,i,s,b} \\ & + \sum_{t,i,j,s} ic_{t,i,j,s} \cdot n^{cap}_{t,i,j,s} \cdot \frac{q(1+q)^{\widehat{t_j}}}{(1+q)^{\widehat{t_j}} - 1} \\ & + \sum_{t,i,s,c} - icf_{i,c} \cdot mc_{t,i,s} \cdot \pi_{t,i,s,c} \\ & + \sum_{t,i,j,s,c} - icf_{i,c} \cdot ic_{t,i,s} \cdot n^{cap}_{t,i,j,s,c} \cdot \frac{q(1+q)^{\widehat{t_j}}}{(1+q)^{\widehat{t_j}} - 1} \end{aligned} \tag{2}$$

subject to

$$\delta_{t,s,c} = \sum_i \pi_{t,i,s,c}, \; \forall (t, i, s = 1..5, c) \in (T, I, S, C) \tag{3}$$

$$\sum_c \pi_{t,i,s,c} = \pi_{t,i,s}, \; \forall (t, i, s = 1..5, c) \in (T, I, S, C) \tag{4}$$

$$n^{cap}_{t,i,s,c} \cdot \kappa_{t,s} = \pi_{t,i,s,c}, \; \forall (t, i, s = 1..5, c) \in (T, I, S, C) \tag{5}$$

$$\sum_c n^{cap}_{t,i,s,c} = n^{cap}_{t,i,s,} \; \forall (t, i, s = 1...5, c) \in (T, I, S, C) \tag{6}$$

In order to incorporate consumer choice, four additional restrictions were added to the original model formulation, which is described in Jordan et al. 26. The heat demand δ in each cluster c of the five sub-sectors s needs to be met by the sum of the heat produced π of all technologies i within one cluster (3). The sum of heat produced over all clusters needs to equal the heat production within its sub-sector (4). The sum of heating systems installed n^{cap} multiplied by their individual capacity κ equals the yearly heat production of each technology within its cluster (5). Equation (6) is equivalent to equation (4) in relation to n^{cap}. In each sub-sector, premature decommissioning of heating systems is only allowed for fossil fuel technologies and limited to 1%/a. This restriction is not set within the clusters, i.e. consumers/heating systems can switch clusters over time within one sub-sector.

2.4. Scenarios and sensitivity analysis

In this study, a business as usual (BAU) and an ambitious measures scenario (AMS) are analyzed, both calculated with and without consumer choice. In the BAU scenario energy prices are kept at a constant level and no CO^2 pricing is in place. Additionally, current investment incentives for heating technologies are considered (except for biogas feed-in compensation) and a moderate refurbishment rate is assumed.

In the AMS scenario, energy only prices increase moderately and an ambitious pricing of CO_2 is set, increasing constantly up to 200

€/tCO^{2}eq in 2050. The CO^2 price increase is derived from current scenario analyses that project prices in that range to reach a 95% reduction target (Repenning et al., 2015). Furthermore, all planned future incentives in the heat sector as well as an ambitious refurbishment rate are set in the AMS scenario. The main scenario parameter settings are shown in Table 4.

A few parameters are set equally in all four scenarios: in the power sector GHG emissions are assumed to decrease linearly up until 2050 (17 gCO^{2}eq./kWh in 2050). Further, the national potential for biomass residues is derived from the upper and lower range of current energetic use and the exploitable potential described in Brosowski et al. (2019) and DBFZ (2019), see Fig. 3. The potential of available land for energy crops is set to decrease linearly to 0 ha in 2050. From the overall available biomass potential (residues and energy crops), a share of $\sim$ 70% is pre-allocated to the heat sector (incl. CHP applications) within the model, according to the method described in Jordan et al. 26.

Finally, the variance-based sensitivity analysis of Sobol' was applied to the model to systematically assess which uncertain input parameters affect the model output. A particular focus is placed on the effect of applying consumer choice within the model and on viewing it in interaction with the other uncertain input parameters. The uncertainty range in which 45 input parameters were varied is documented in the supplementary material. A detailed description of how the Sobol' method is applied to the optimization model can be found in Jordan et al. 27.

3. Results and discussion

The results show that future market shares for log wood, wood pellet and also heat pump technology are less represented in the BAU scenario without consumer choice being applied, see Fig. 4. A typical picture emerges from the optimization results: only a few technologies gain major market shares compared to the broader “portfolio” of the start year, 2015. When heterogeneous consumer choice is incorporated into the BAU scenario, the market shares of the start year portfolio remain more or less constant, especially for the private household sector. In this case, the optimization model delivers more diverse projections.

A more detailed depiction of market shares for bioenergy shows the effect on competitiveness of the individual bioenergy technology concepts in the private household sector, see Fig. 5. Without applying consumer choice in the model, none of the recent bioenergy technology concepts remains competitive and all of the available solid biomass is distributed in high temperature industry applications, see Fig. 4. This is in line with findings from previous studies, where this technology option was found to be a robust result (Jordan et al., 2020). In contrast, when applying consumer choice, log wood and wood pellet technologies in the private household sector maintain a constant market share or increase their market share slightly. Here, the type of technology remains the same but a switch in the technology deployment concept occurs: the use of log wood switches from gas boilers combined with a log wood stove and solar thermal system to being used in log

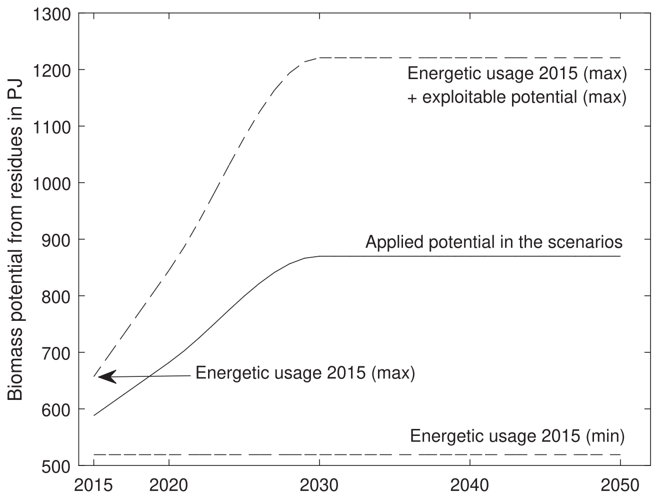

Fig. 3. Applied biomass potential from residues derived from national monitoring of residues (Brosowski et al., 2019; DBFZ, 2019). The range between the upper and lower curve is investigated in the sensitivity analysis.

wood gasification boilers combined with solar thermal. The use of pellets switches from pellet boilers in the private household and trade/commerce sector to use in pellet burners with an integrated buffer combined with solar thermal.

A similar picture emerges for the ambitious measures scenario. Without applying consumer choice, biomass is shown to be used almost entirely by industry while the use of biomass in the private household sector phases out almost completely, see Figs. 4 and 5. If consumer choice is applied, the general trend remains that most of the biomass is used competitively in high temperature industry applications. Furthermore, bioenergy is used in the private household sector, especially in the form of log wood. In this case, wood pellet technologies do not remain competitive.

A detailed depiction of the market shares within the consumer segments of the five single-family housing sub-sectors shows that the method of implementing consumer choice leads to the expected results, see Figs. 6 and 7. In three out of five sub-sectors, the technology types with the largest market shares are those which, according to the findings of Michelsen and Madlener (2013), are preferred by the consumers of the different segments C1..C3. Exceptions are the sub-sectors with a system size of 2.5 and 5 kW. This finding, contrary to what would be expected, can be explained on the basis that these sub-sectors represent a high insulation standard: in this case the price advantage of heat pumps or gas technologies overrule the non-economic factors. In addition, the survey on which the identified consumer choices are based was conducted in 2010. At that time, houses with such high insulation standards were underrepresented and therefore did not fall within the scope of the survey.

In general, we can see that implementing consumer choice leads to a broader diversity in technology market shares while the

Table 4
Setting of the main scenario parameters.

	Business as usual (BAU)	Ambitious measures scenario (AMS)
Stock market power price	32 €/MWh	32 €/MWh
Gas price (energy only)	19.8 €/MWh	19.8 → 26,6 €/MWh
Biomass price increase	0%/a	1%/a
CO^2 price	not in place	act. status → 200 €/tCO^{2}eq.
Refurbishment	1−2%/a	2−3%/a
Incentives	Investment subsidies valid until 2019	Investment subsidies valid from 2020
Consumer choice	yes/no	yes/no

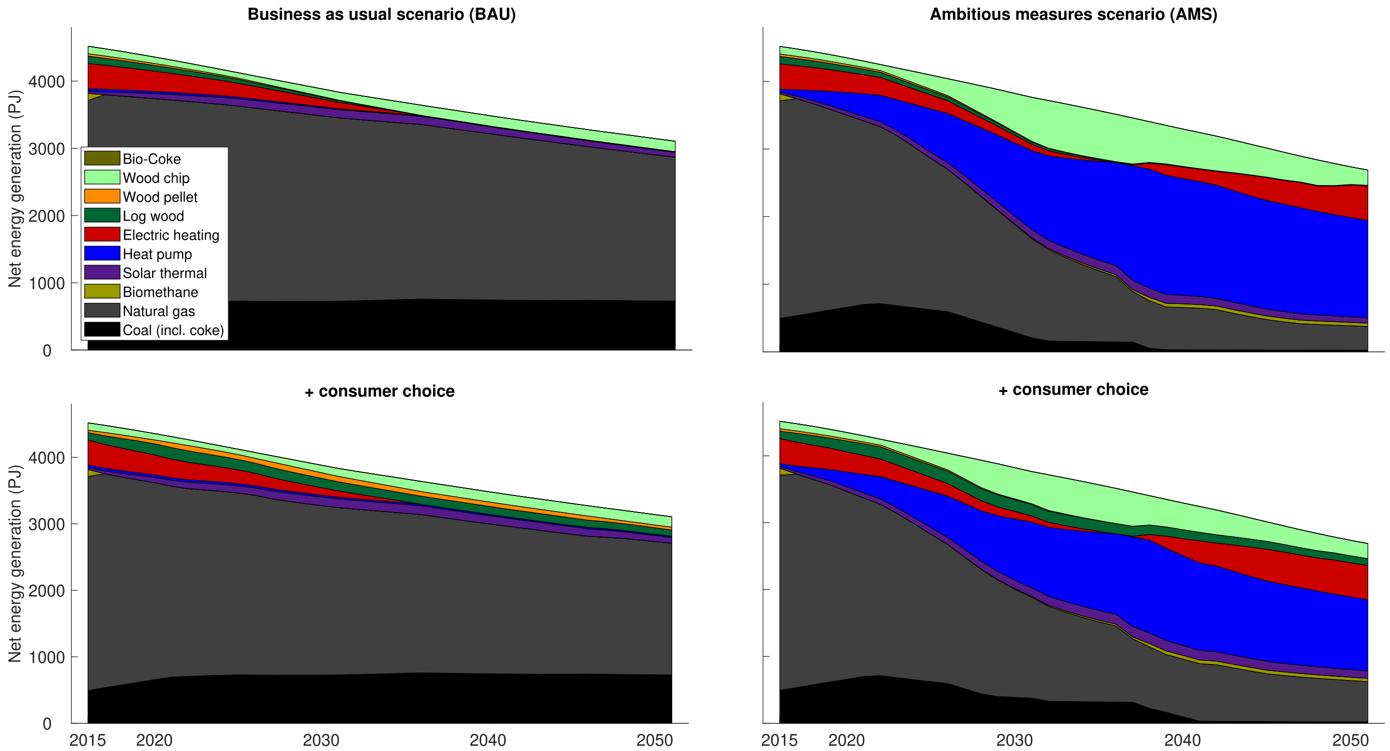

Fig. 4. Model resulting development of the technology market shares for the complete heat sector for the different scenarios in a yearly resolution.

market penetration of heating technologies shows a gradual and smooth development. The model outcome shows a more plausible development than in the model runs without consumer choice applied. However, this conclusion has not been subjected to validation and would require historical data and a calibration of the model.

Based on this study's findings, one could conclude that log wood market shares have been underrepresented in previous studies. Jordan et al. (2019) concluded that log wood technologies are the least cost-competitive wood-based bioenergy technology, as their market share decreases rapidly in the model with decreasing biomass potential in the scenarios investigated. In addition, a sensitivity analysis found that the use of biomass in large amounts of log wood is not a robust result, as indicated by the low market penetration of high log wood shares over a broad range of outcomes (Jordan et al., 2020). In this study, we show that the inclusion of consumer choice has an impact on market shares for log wood in both the scenarios investigated and the sensitivity analysis, see

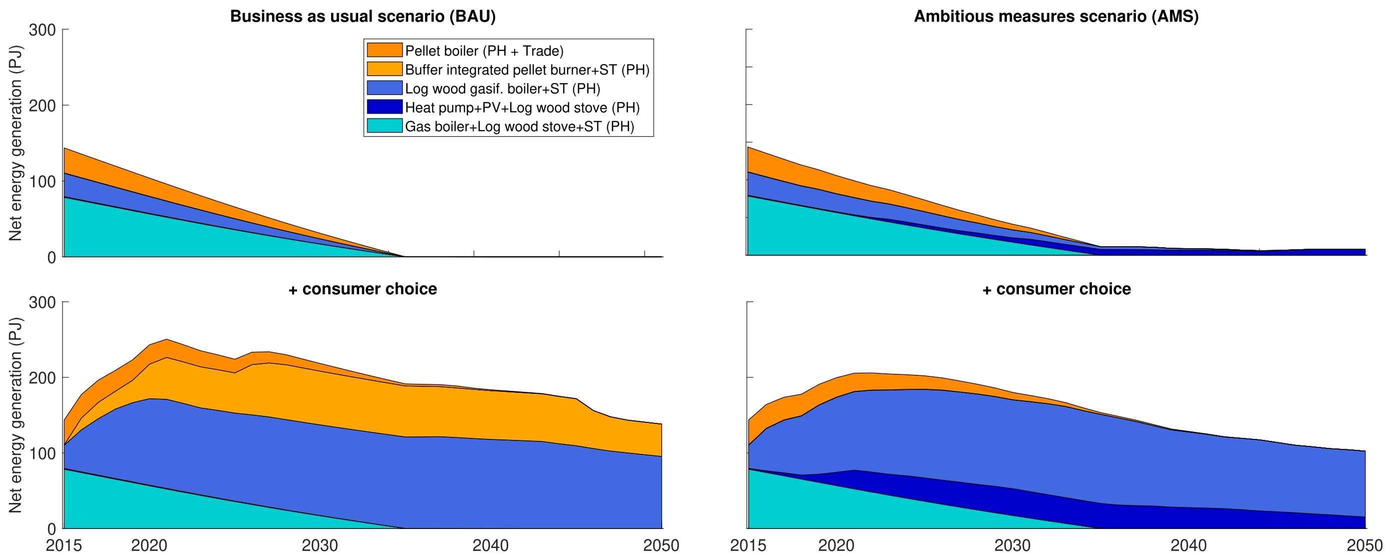

Fig. 5. Net energy market shares of the relevant bioenergy technologies in the private household sector. Within the figure only the relevant bioenergy technology concepts are shown, leaving out fossil references, alternative renewable technologies and unrelevant bioenergy concepts. For hybrid systems, only the biomass net energy shares of the concepts are displayed in order to have a depiction of the biomass utilization. Ind = Industry; DH = District Heating; PH = Private Households; CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST = Solar Thermal.

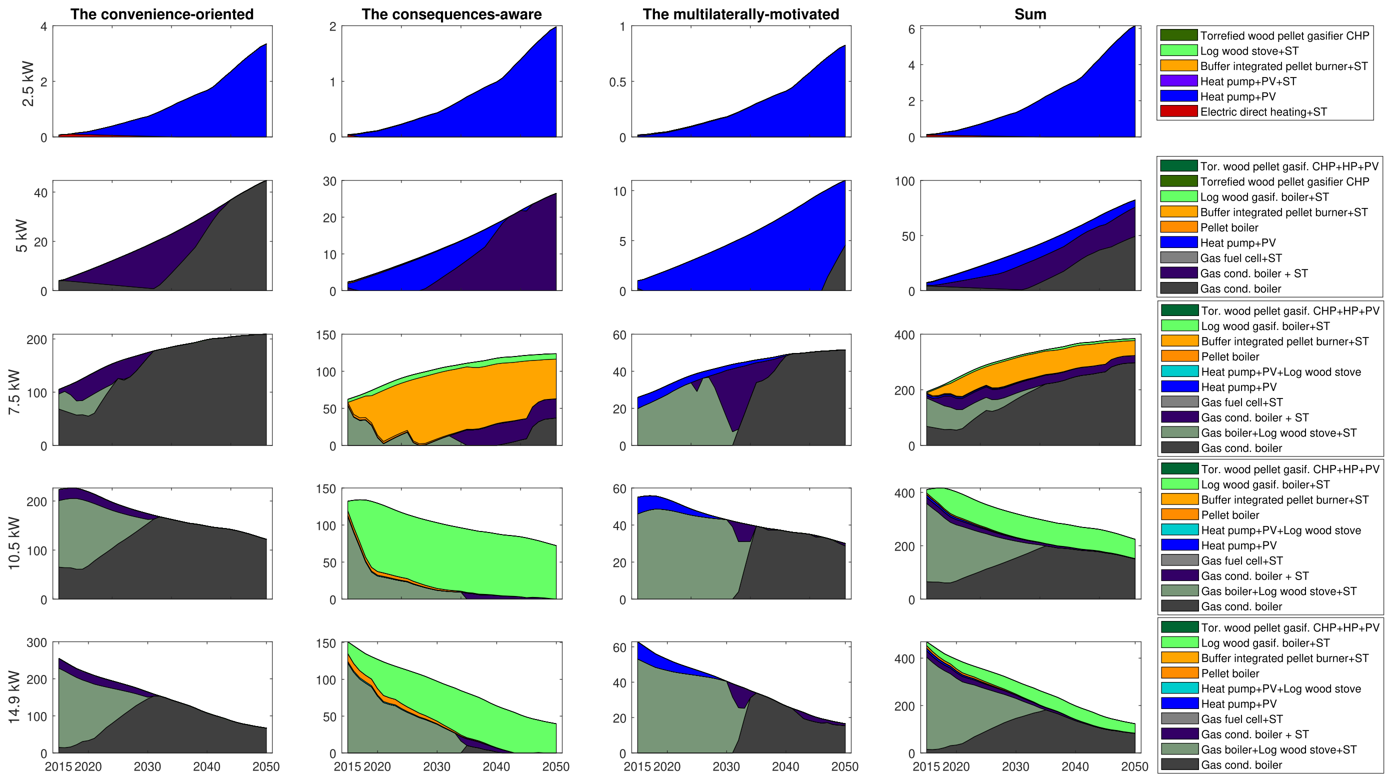

Fig. 6. Net energy technology market shares in the consumer segments of the five single-family sub-sectors in the BAU scenario considering consumer choice (in PJ). CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST = Solar Thermal.

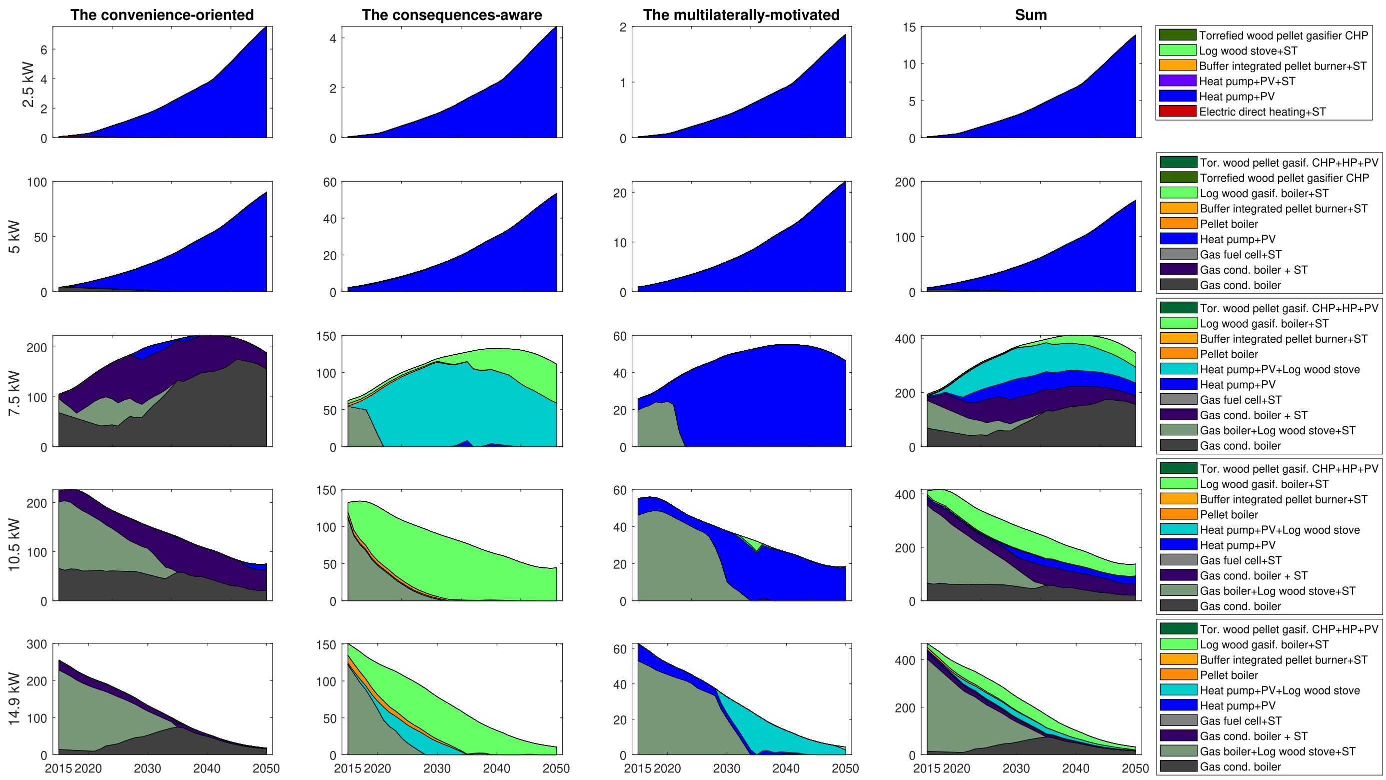

Fig. 7. Net energy technology market shares in the consumer segments of the five single-family sub-sectors in the ambitious measures scenario considering consumer choice (in PJ). CHP = Combined Heat and Power; HP = Heat Pump; PV = Photovoltaic; ST = Solar Thermal.

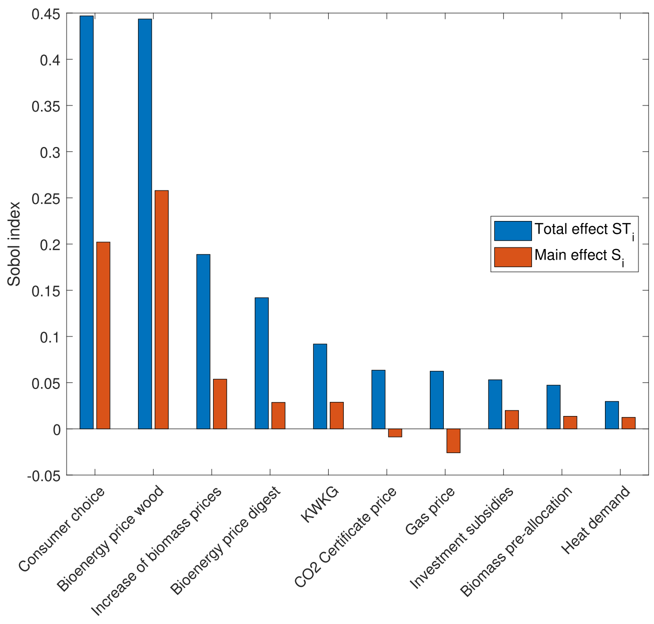

Fig. 8. Sobol' indices on log wood market shares from 2030 to 2050 for the most influential input parameters. Both Sobol' indices range from 0 to 1. $S_{Ti} \geq S_i \geq 0$. If $S_{Ti} = S_i = 0$ the parameter is non-influential. If $S_{Ti} = S_i$ there is no interaction of the i^{th} parameter with other parameters. In this case S_i can become negative, as some of the varied input factors are correlated. For a detailed description of this phenomenon see (Wei et al., 2015).

Fig. 8. The integration of consumer choice is found to influence market shares for log wood significantly, represented by a high Sobol' index.

It should be noted that investment considerations with regard to log wood technologies were not differentiated from those for wood pellet technologies in the survey conducted by Michelsen and Madlener (2012). Consequently, the indirect cost factor in the model was equalized for both the wood pellet and log wood options, which is a debatable move. Consumer choice is driven by economic and ecological factors as well as by comfort and individual factors, among others. Pellet and log wood technologies, for example, have different perceived comfort characteristics. While a pellet burner runs automatically, a log wood stove has to be piled up at least once a day. On the other hand, log wood might be readily available to forest owners (or those with authorized forest access), leading to the installation of a log wood heating system. This should be kept in mind when interpreting the results from this study. For future studies it would be helpful to conduct a more detailed survey on homeowners' investment decisions in relation to more differentiated heating technologies.

3.1. Limitations

Although we have been able to show that the integration of consumer choice leads to a broader diversity in market shares for different heating technologies and the model delivers more plausible results, the data available for doing so are subject to uncertainty and the methodological options are limited. In this study, the survey-based empirical data are limited to the consumer behavior of homeowners in single-family houses. Data on consumer behavior for multi-family houses or the heat consuming industry are not available on a national scale. It might be assumed that in these sectors investment decisions are driven purely by economical motivations. A review of company guidelines, ISO standardizations, annual and sustainability reports of the major heat consuming companies in the German industry sector did not lead to any conclusive findings that factors other than economic ones influence decisions on heating technology investment.

In addition, the data available for single-family houses are from 2010. Behavior change over the course of time, see e.g. Borgstedt et al. (2010). This factor can have a decisive impact, especially when modeling a time frame up to 2050. However, a projection of future consumer behavior in relation to investment decisions regarding heating system is not currently available. The identification of factors that drive such change could help to improve such projections. For future research, it would be helpful to have empirical data on the consumer behavior of multi-family house owners and stakeholders in the heat consuming industry in order to improve the representation of consumer choice for the heat sector as a whole.

The method used to integrate consumer choice into the optimization model is in some ways a novel approach. The concept of creating different consumer segments to represent the heterogeneity in consumer choice, however, is an established method (Bunch et al., 2015; Cayla and Maïzi, 2015; Daly et al., 2014; Li and Strachan, 2019; Li et al., 2018; McCollum et al., 2017; Ramea et al., 2018; Tattini et al., 2018). Applying indirect or intangible or disutility costs in these segments is also a common approach. It was not possible, however, to identify a standard methodological approach for calculating the indirect costs, representing consumer investment decisions. In all reviewed papers, indirect costs were calculated in a unique way for each case driven by the country specific influencing factors. A simple transfer of the method for calculating indirect costs to the German case is therefore not applicable. In this study, an increase in the probability of a higher market share is translated into indirect costs. This method is derived from the economic theory which states that the market shares of two technologies should be inversely related to their relative cost (Zweifel et al., 2017). This methodological step can be discussed and, as stated in Section 2.3, a calibration of the factor g with historical data would be desirable. However, methodological alternatives are rare. Hedenus et al. (2013) describe the use of distribution functions to make the model's results more diverse and to restrict the diffusion of single technologies. However, a method showing how to combine distribution functions with empirical data on consumer choice is, to the authors' knowledge, not available.

The tenant-landlord dilemma, describes the circumstance in rented houses/flats that investments in renewable energy are not made because the landlord cannot achieve a return on his investment in the long term, while the tenant would benefit. This dilemma could not be represented in this study and should be in the scope of future studies. However, this problem occurs mostly in multi-family houses, for which empirical data on consumer behavior was not available for Germany.

Some scholars have wondered whether some of the techniques introduced have in fact changed the modeling paradigm by introducing consumer choice into a pure cost minimization model (DeCarolis et al., 2017). They conclude that the theoretical basis needs to be better understood and that more empirical data and case studies are required to improve the integration of consumer choice in ESOMs. Agent-based models are suited to process probability data as marginal effects, for example, see Steinbach and Staniaszek (2015). With agent-based models, microeconomic behavior can be modeled in a way that reveals macroeconomic effects. However, optimal economic transition pathways cannot be determined using this model type, and if the quality of the solution is important, traditional approaches such as optimization tend to outperform agent-based approaches (Barbati et al., 2012).

4. Conclusions

In this study, consumer behavior was integrated for the first time into an ESOM for the German heat sector. The model enabled consumer heterogeneity and behavioral factors influencing investment decisions other than cost minimization to be represented. The results show that the integration of consumer choice produces a broader range of technologies with market shares and thus more plausible results. Established methods representing consumer heterogeneity and a novel approach for calculating indirect costs were combined in the model to represent consumer investment decisions.

We were able to show in the case of Germany and in comparison to previous studies that solid biomass is not only optimally distributed in (high temperature) industry applications. The results indicate that, in the private household sector, a demand for bioenergy may persist in future energy scenarios: this therefore needs to be addressed. In particular, the future role of log wood and pellet technologies may have been underestimated in previous studies and should be discussed when designing policies. Still, these findings need to be handled with care, since the empirical data basis and the methodological basis is limited.

Another finding leads to the conclusion that in houses with high insulation standards, economic factors are predominant and exceed the willingness to pay for other, preferred technologies. In the future, the economic advantages of heat pumps in well-insulated houses overrule non-economic preferences and lead to exclusive market shares of heat pumps in these sub-sectors.

The results obtained from the study offer a broader basis for the design of a cleaner heat sector. The literature discusses how consumers can be encouraged to adopt cleaner heating systems. For this purpose, policy makers need to adopt a holistic view that includes non-economic factors and captures the heterogeneity of actors and their preferences. The results of this study provide a broader knowledge base that can help policy makers decide on deployment schemes for cleaner heat production. In particular, the conditions for future use of biomass in the German heat sector could be improved. In previous studies using pure cost optimized scenario projections for the future use of biomass, high temperature industry applications were identified as the cost optimal option for biomass. Our study shows that when non-economic behavior factors affecting consumer choice are considered, private households may demand an additional $\sim 100 - 200$ PJ/a of log wood. This projection of future demand should be discussed when designing technical schemes and policies for implementation. For the heat consuming industry we conclude that in a future heat sector based on renewable energy supplies, a competitive demand might persist for the limited biomass available in Germany. At the same time, according to the results of this study, there will continue to be demand for small-scale bioenergy combustion plants in the future.

In addition, the study contributes to the development of methods in terms of improving the integration of behavioral factors of consumer choice into ESOMs. In literature, a demand for further case studies is described (DeCarolis et al., 2017), to which this conducted study contributes.

For future studies, the extended model provides an opportunity to describe the effect of different funding instruments given the factor of consumer choice. For this purpose, more recent and detailed empirical data on homeowners' investment decisions around a broader range of heating technologies would be helpful. It would also be helpful to advance the methodology further, e.g. with regard to calibration, in order to provide policy insights with a high level of confidence.

CRediT authorship contribution statement

Matthias Jordan: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. **Charlotte Hopfe:** Investigation, Writing – review & editing. **Markus Millinger:** Conceptualization, Writing – review & editing, Supervision. **Julian Rode:** Methodology, Writing – review & editing. **Daniela Thrän:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the Federal Ministry for Economic Affairs and Energy (03KB113B) and the Helmholtz Association of German Research Centres, with support provided by the Helmholtz Impulse and Networking Fund through the Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE). Declarations of interest: none.

We are grateful to Öko-Institut e.V. for sharing the heat demand data calculated using B-STar (Building Stock Transformation Model), which were used in this study for the defined household, trade and commerce, and district heating markets (Koch et al., 2018).

Our thanks go also to Volker Lenz for providing technical and economic technology data on which this and previous studies are based.

Thank you to Anneliese Koppelt for conducting a review of company guidelines, ISO standardizations, and annual and sustainability reports of the major heat consuming companies in the German industrial sector.

Kathleen Cross helped improve the language.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126319.

References

Backhaus, Klaus, Erichson, Bernd, Wulff, Plinke, Weiber, Rolf, 2016. Multivariate Analysis Methods (Multivariate Analysemethoden). Springer Berlin Heidelberg, Berlin, Heidelberg, ISBN 978-3-662-46075-7. https://doi.org/10.1007/978-3-662-46076-4.

Barbati, M., Bruno, G., Genovese, A., 2012. Applications of agent-based models for optimization problems: a literature review. Expert Syst. Appl. 39 (5), 6020–6028. https://doi.org/10.1016/j.eswa.2011.12.015. ISSN 9574174.

Borgstedt, Silke, Christ, Tamina, and Reusswig, Fritz, 2010, Environmental awareness in germany 2010 (Umweltbewusstsein in Deutschland 2010): Results of a representative population survey (Ergebnisse einer repräsentativen Bevölkerungsumfrage). URL https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4045.pdf.

Braun, Frauke G., 2010. Determinants of households' space heating type: a discrete choice analysis for German households. Energy Pol. 38 (10), 5493–5503. https://doi.org/10.1016/j.enpol.2010.04.002. ISSN 3014215.

Brosowski, André, Krause, Tim, Mantau, Udo, Mahro, Bernd, Noke, Anja, Richter, Felix, Raussen, Thomas, Roland, Bischof, Hering, Thomas, Blanke, Christian, Paul, Müller, Thrän, Daniela, 2019. How to measure the impact of biogenic residues, wastes and by-products: development of a national resource monitoring based on the example of Germany. Biomass Bioenergy 127, 105275. https://doi.org/10.1016/j.biombioe.2019.105275. ISSN 9619534.

David Bunch, Kalai Ramea, Sonia Yeh, and Christopher Yang, 2015, Incorporating Behavioral Effects from Vehicle Choice Models into Bottom-Up Energy Sector Models.

Bundesministerium für Wirtschaft und Energie, 2019, Energy data (Energiedaten): Complete edition (Gesamtausgabe). URL https://www.bmwi.de/Redaktion/DE/Downloads/Energiedaten/energiedaten-gesamt-pdf-grafiken.pdf?

__blob=publicationFile&v=40.
Bundesverband des Schornsteinfegerhandwerks - Zentralinnungsverband, 2018 , Surveys of the chimney sweep trade (Erhebungen des Schornsteinfegerhandwerks).
Cayla, Jean-Michel, Maïzi, Nadia, 2015. Integrating household behavior and heterogeneity into the TIMES-Households model. Appl. Energy 139, 56–67. https://doi.org/10.1016/j.apenergy.2014.11.015.
Cayla, Jean-Michel, Osso, Dominique, 2013, Does energy efficiency reduce inequalities? Impact of policies in residential sector on household budget. URL https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2013/5a-cutting-the-energy-use-of-buildings-projects-and-technologies/does-energy-efficiency-reduce-inequalities-impact-of-policies-in-residential-sector-on-household-budget/.
Cherp, Aleh, Vinichenko, Vadim, Jewell, Jessica, Brutschin, Elina, Sovacool, Benjamin, 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. Energy Research & Social Science 37, 175–190. https://doi.org/10.1016/j.erss.2017.09.015. ISSN 22146296. https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4045.pdf.
Consentec GmbH, Fraunhofer ISI, 2018. Evaluation of reference studies and scenario analyses on the future development of grid charges for electricity (BMWi-Vorhaben Netzentgelte: Auswertung von Referenzstudien und Szenarioanalysen zur zukünftigen Entwicklung der Netzentgelte für Elektrizität). URL https://www.agora-energiewende.de/fileadmin2/Projekte/2015/EEG-Kosten-bis-2035/Agora_EEG_Kosten_2035_web_05052015.pdf.
Daly, Hannah E., Ramea, Kalai, Chiodi, Alessandro, Yeh, Sonia, Gargiulo, Maurizio, Gallachóir, Brian Ó., 2014. Incorporating travel behaviour and travel time into TIMES energy system models. Appl. Energy 135, 429–439. https://doi.org/10.1016/j.apenergy.2014.08.051.
DBFZ, 2019. Data repository: ressource database (ressourcendatenbank). http://webapp.dbfz.de/resources.
DeCarolis, Joseph, Daly, Hannah, Dodds, Paul, Keppo, Ilkka, Li, Francis, McDowall, Will, Pye, Steve, Strachan, Neil, Trutnevyte, Evelina, Usher, Will, Winning, Matthew, Yeh, Sonia, Zeyringer, Marianne, 2017. Formalizing best practice for energy system optimization modelling. Appl. Energy 194, 184–198. https://doi.org/10.1016/j.apenergy.2017.03.001.
Decker, Thomas Anton, 2010. Consumer behavior when buying a private consumer good using heating as an example (Verbraucherverhalten beim Kauf eines privaten Gebrauchsguts am Beispiel Heizung), volume 3 of *Nachwachsende Rohstoffe in Forschung und Praxis*. Attenkofer, Straubing. https://mediatum.ub.tum.de/?id=957129.
Decker, Thomas, Menrad, Klaus, 2015. House owners' perceptions and factors influencing their choice of specific heating systems in Germany. Energy Pol. 85, 150–161. https://doi.org/10.1016/j.enpol.2015.06.004. ISSN 3014215.
Decker, Thomas, Zapilko, Marina, Menrad, Klaus, 2009. Purchase Behaviour related to Heating Systems in Germany with Special Consideration of Consumers' Ecological Attitudes. Energy Engineering, Economics and Policy (EEEP) Conference Orlando (USA), 13th July 2009. https://doi.org/10.22004/ag.econ.137596.
DiClemente, Diane F., Hantula, Donald A., 2003. Applied behavioral economics and consumer choice. J. Econ. Psychol. 24 (5), 589–602. https://doi.org/10.1016/S0167-4870(03)00003-5. ISSN 1674870.
ETA-Florence Renewable Energies, 2019. In: Competitive Biomass Key Applications to Fulfill Climate Targets in the German Heat Sector: Findings from Optimization Modelling. ETA-Florence Renewable Energies. https://doi.org/10.5071/27thEUBCE2019-5BV.3.10. In: http://www.etaflorence.it/proceedings/?detail=16385.
Gossen, Maike, Nischan, Carolin, 2014. Regional Differences in the Perception of Energetic Refurbishment (Regionale Differenzen in der Wahrnehmung Energetischer Sanierung): Results of a Qualitative Survey of Building Owners on Energetic Refurbishment in Two Different Regions. (Ergebnisse einer Qualitativen Befragung von GebäudeeigentümerInnen zu Energetischer Sanierung in Zwei Unterschiedlichen Regionen). URL https://www.gebaeude-energiewende.de/data/gebEner/user_upload/Dateien/GEW_AP1_Ergebnisbericht_Interviews_final_141126.pdf.
Götz, Philipp, Henkel, Johannes, and Lenck, Thorsten, 2013. Relationship between power exchange prices and end customer prices (Zusammenhang von Strombörsenpreisen und Endkundenpreisen): Study commissioned by Agora Energiewende (Studie im Auftrag der Agora Energiewende). URL https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/netzentgelte-auswertung-von-referenzstudien.pdf?__blob=publicationFile&v=6.
Haller, Markus, Kleiner, Mara Marthe, Graichen, Verena, 2015, The development of renewable act costs until 2035 (Die Entwicklung der EEG-Kosten bis 2035): how the expansion of renewables works along the long-term goals of the energy transition (Wie der Erneuerbaren-Ausbau entlang der langfristigen Ziele der Energiewende wirkt). URL https://www.agora-energiewende.de/fileadmin2/Projekte/2015/EEG-Kosten-bis-2035/Agora_EEG_Kosten_2035_web_05052015.pdf.
Hedenus, Fredrik, Johansson, Daniel, Lindgren, Kristian, 2013. A critical assessment of energy-economy-climate models for policy analysis. J. Appl. Econ. Bus. Res. 3 (2), 118–132. http://www.aebrjournal.org/uploads/6/6/2/2/6622240/joaebrjune2013_118_132.pdf.
Horne, Matt, Jaccard, Mark, Tiedemann, Ken, 2005. Improving behavioral realism in hybrid energy-economy models using discrete choice studies of personal transportation decisions. Energy Econ. 27 (1), 59–77. https://doi.org/10.1016/j.eneco.2004.11.003. ISSN 01409883.
Jordan, Matthias, Lenz, Volker, Millinger, Markus, Oehmichen, Katja, Thrän, Daniela, 2019. Future competitive bioenergy technologies in the German heat sector: findings from an economic optimization approach, 116194 Energy 189. https://doi.org/10.1016/j.energy.2019.116194. ISSN 3605442.
Jordan, Matthias, Millinger, Markus, Thrän, Daniela, 2020. Robust bioenergy technologies for the German heat transition: a novel approach combining optimization modeling with Sobol' sensitivity analysis. Appl. Energy 262, 114534. https://doi.org/10.1016/j.apenergy.2020.114534.
Kahneman, Daniel, Tversky, Amos, 1984. Choices, values, and frames. Am. Psychol. 39 (4), 341–350. https://doi.org/10.1037/0003-066X.39.4.341. ISSN 0003-066X.
Kennedy, Matthew, Basu, Biswajit, 2013. A study on the implementation of renewable heating technologies in the domestic sector in Ireland with implications on consumers' decision-making. J. Clean. Prod. 44, 133–142. https://doi.org/10.1016/j.jclepro.2013.01.018. ISSN 09596526.
Kennedy, Matthew, Dinh, Van-Nguyen, Basu, Biswajit, 2016. Analysis of consumer choice for low-carbon technologies by using neural networks. J. Clean. Prod. 112, 3402–3412. https://doi.org/10.1016/j.jclepro.2015.10.035. ISSN 09596526.
Khan, Khalid S., Kunz, Regina, Kleijnen, Jos, Antes, Gerd, 2003. Five steps to conducting a systematic review. J. Roy. Soc. Med. 96.
Klein, Martin, Deissenroth, Marc, 2017. When do households invest in solar photovoltaics? An application of prospect theory. Energy Pol. 109, 270–278. https://doi.org/10.1016/j.enpol.2017.06.067. ISSN 3014215.
Matthias Koch, Klaus Hennenberg, Katja Hünecke, Markus Haller, and Tilman Hesse, 2018, Role of bioenergy in the electricity and heating market until 2050, taking into account the future building stock (Rolle der Bioenergie im Strom- und Wärmemarkt bis 2050 unter Einbeziehung des zukünftigen Gebäudebestandes). URL https://www.energetische-biomassenutzung.de/fileadmin/Steckbriefe/dokumente/03KB114_Bericht_Bio-Strom-W%C3%A4rme.pdf.
Korcaj, Liridon, Hahnel, Ulf J., Spada, Hans, 2015. Intentions to adopt photovoltaic systems depend on homeowners' expected personal gains and behavior of peers. Renew. Energy 75, 407–415. https://doi.org/10.1016/j.renene.2014.10.007. ISSN 09601481.
Lenz, Volker, Jordan, Matthias, 2019. Technical and Economic Data of Renewable Heat Supply Systems for Different Heat Sub-sectors. https://doi.org/10.17632/v2c93n28rj.2.
Lenz, Volker, Thrän, Daniela, 2015. Flexible heat provision from biomass. In: Thrän, Daniela (Ed.), Smart Bioenergy. Springer International Publishing, Cham, ISBN 978-3-319-16192-1, pp. 83–105. https://doi.org/10.1007/978-3-319-16193-8.
Li, Francis G.N., Strachan, Neil, 2019. Take me to your leader: using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways. Energy Research & Social Science 51, 67–81. https://doi.org/10.1016/j.erss.2018.12.010. ISSN 22146296.
Li, Pei-Hao, Keppo, Ilkka, Strachan, Neil, 2018. Incorporating homeowners' preferences of heating technologies in the UK TIMES model. Energy 148, 716–727. https://doi.org/10.1016/j.energy.2018.01.150. ISSN 3605442.
McCollum, David, Krey, Volker, Kolp, Peter, Nagai, Yu, Riahi, Keywan, 2014. Transport electrification: a key element for energy system transformation and climate stabilization. Climatic Change 123 (3–4), 651–664. https://doi.org/10.1007/s10584-013-0969-z. ISSN 0165–0009.
McCollum, David L., Wilson, Charlie, Pettifor, Hazel, Ramea, Kalai, Krey, Volker, Riahi, Keywan, Bertram, Christoph, Lin, Zhenhong, Edelenbosch, Oreane Y., Fujisawa, Sei, 2017. Improving the behavioral realism of global integrated assessment models: an application to consumers' vehicle choices. Transport. Res. Transport Environ. 55, 322–342. https://doi.org/10.1016/j.trd.2016.04.003. ISSN 13619209.
Michelsen, Carl Christian, Madlener, Reinhard, 2012. Homeowners' preferences for adopting innovative residential heating systems: a discrete choice analysis for Germany. Energy Econ. 34 (5), 1271–1283. https://doi.org/10.1016/j.eneco.2012.06.009. ISSN 1409883.
Michelsen, Carl Christian, Madlener, Reinhard, 2013. Motivational factors influencing the homeowners' decisions between residential heating systems: an empirical analysis for Germany. Energy Pol. 57, 221–233. https://doi.org/10.1016/j.enpol.2013.01.045. ISSN 3014215.
Michelsen, Carl Christian, Madlener, Reinhard, 2016. Switching from fossil fuel to renewables in residential heating systems: an empirical study of homeowners' decisions in Germany. Energy Pol. 89, 95–105. https://doi.org/10.1016/j.enpol.2015.11.018. ISSN 3014215.
Michelsen, Carl Christian, Madlener, Reinhard, 2017. Homeowner satisfaction with low-carbon heating technologies. J. Clean. Prod. 141, 1286–1292. https://doi.org/10.1016/j.jclepro.2016.09.191. ISSN 9596526.
Millinger, Markus, 2019. BioENergyOPTimisation Model. https://doi.org/10.5281/zenodo.2812986.
Millinger, Markus, Meisel, Kathleen, Budzinski, Maik, Thrän, Daniela, 2018. Relative greenhouse gas abatement cost competitiveness of biofuels in Germany. Energies 11 (3), 615. https://doi.org/10.3390/en11030615. ISSN 1996–1073.
Millinger, M., Meisel, K., Thrän, D., 2019. Greenhouse gas abatement optimal deployment of biofuels from crops in Germany. Transport. Res. Transport Environ. 69, 265–275. https://doi.org/10.1016/j.trd.2019.02.005. ISSN 13619209.
Mills, Bradford F., Schleich, Joachim, 2009. Profits or preferences? Assessing the adoption of residential solar thermal technologies. Energy Pol. 37 (10), 4145–4154. https://doi.org/10.1016/j.enpol.2009.05.014. ISSN 3014215.
Ramea, Kalai, Bunch, David S., Yang, Christopher, Yeh, Sonia, Ogden, Joan M., 2018.

Integration of behavioral effects from vehicle choice models into long-term energy systems optimization models. Energy Econ. 74, 663–676. https://doi.org/10.1016/j.eneco.2018.06.028. ISSN 1409883.
Repenning, Julia, Emele, Lukas, Blanck, Ruth, Böttcher, Hannes, Dehoust, Günter, Förster, Hannah, Greiner, Benjamin, Harthan, Ralph, Hennenberg, Klaus, Hermann, Hauke, Jörß, Wolfram, Loreck, Charlotte, Ludig, Sylvia, Matthes, Felix, Scheffler, Margarethe, Schumacher, Katja, Wiegmann, Kirsten, Zell-Ziegler, Carina, Braungardt, Sibylle, Eichhammer, Wolfgang, Elsland, Rainer, Fleiter, Tobais, Hartwig, Johannes, Kockat, Judit, Pfluger, Ben, Schade, Wolfgang, Schlomann, Barbara, Sensfuß, Frank, and Ziesing, Hans-Joachim, 2015, Climate protection scenario 2050 (Klimaschutzszenario 2050): 2. Endbericht -Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit. URL https://www.oeko.de/oekodoc/2451/2015-608-de.pdf.
Rönsch, Cornelia, 2019. Development of a method to use the data of the chimney sweep trade for the energy industry reporting (Entwicklung einer Methode zur Verwendung der Daten des Schornsteinfegerhandwerks für die energiewirtschaftliche Berichterstattung): PhD thesis (Dissertationsschrift). https://www.dbfz.de/fileadmin/user_upload/Referenzen/DBFZ_Reports/DBFZ_Report_34.pdf.
Steinbach, Jan, Staniaszek, Dan, 2015. Discount rates in energy system analysis: discussion paper. http://bpie.eu/uploads/lib/document/attachment/142/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf.
Steinbach, Jan, 2015. Model-based analysis of policy instruments to promote renewable energy and energy efficiency in the building sector (Modellbasierte Untersuchung von Politikinstrumenten zur Förderung erneuerbarer Energien und Energieeffizienz im Gebäudebereich). Dissertation, Fraunhofer-Institut für System- und Innovationsforschung and Fraunhofer IRB-Verlag. http://publica.fraunhofer.de/dokumente/N-385554.html.
Stieß, Immanuel, Dunkelberg, Elisa, 2013. Objectives, barriers and occasions for energy efficient refurbishment by private homeowners. J. Clean. Prod. 48, 250–259. https://doi.org/10.1016/j.jclepro.2012.09.041. ISSN 9596526.
Immanuel Stieß, Victoria van der Land, Barbara Birzle-Harder, Jutta Deffner, 2010, Motives for action, obstacles and target groups for an energetic renovation of buildings (Handlungsmotive, -hemmnisse und Zielgruppen für eine energetische Gebäudesanierung).
Su, Dejin, Zhou, Wenli, Gu, Yuandong, Wu, Bei, 2019. Individual motivations underlying the adoption of cleaner residential heating technologies: evidence from Nanjing, China. J. Clean. Prod. 224, 142–150. https://doi.org/10.1016/j.jclepro.2019.03.113. ISSN 9596526.
Tattini, Jacopo, Ramea, Kalai, Gargiulo, Maurizio, Yang, Christopher, Mulholland, Eamonn, Yeh, Sonia, Karlsson, Kenneth, 2018. Improving the representation of modal choice into bottom-up optimization energy system models – the MoCho-TIMES model. Appl. Energy 212, 265–282. https://doi.org/10.1016/j.apenergy.2017.12.050.
Umweltbundesamt, 2020. Renewable energies in germany (Erneuerbare Energien in Deutschland): Data on development in 2019 (Daten zur Entwicklung im Jahr 2019). URL https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-04-03_hgp-ee-in-zahlen_bf.pdf.
Vainio, Annukka, Anna, Pulkka, Paloniemi, Riikka, Varho, Vilja, Tapio, Petri, 2020. Citizens' sustainable, future-oriented energy behaviours in energy transition, 118801 J. Clean. Prod. 245. https://doi.org/10.1016/j.jclepro.2019.118801. ISSN 9596526.
Venturini, Giada, Tattini, Jacopo, Mulholland, Eamonn, Gallachóir, Brian Ó., 2018. Improvements in the representation of behavior in integrated energy and transport models. International Journal of Sustainable Transportation 13 (4), 294–313. https://doi.org/10.1080/15568318.2018.1466220. ISSN 1556–8318.
Wei, Pengfei, Lu, Zhenzhou, Song, Jingwen, 2015. Variable importance analysis: a comprehensive review. Reliab. Eng. Syst. Saf. 142, 399–432. https://doi.org/10.1016/j.ress.2015.05.018. ISSN 9518320.
Woersdorfer, Julia Sophie, Kaus, Wolfhard, 2011. Will nonowners follow pioneer consumers in the adoption of solar thermal systems? Empirical evidence for northwestern Germany. Ecol. Econ. 70 (12), 2282–2291. https://doi.org/10.1016/j.ecolecon.2011.04.005. ISSN 9218009.
Zundel, Stefan, Stieß, Immanuel, 2011. Beyond profitability of energy-saving measures—attitudes towards energy saving. J. Consum. Pol. 34 (1), 91–105. https://doi.org/10.1007/s10603-011-9156-7. ISSN 0168–7034.
Zweifel, Peter, Praktiknjo, Aaron, Erdmann, Georg, 2017. Energy Economics. Springer Berlin Heidelberg, Berlin, Heidelberg, ISBN 978-3-662-53020-7. https://doi.org/10.1007/978-3-662-53022-1.

Paper 4

Benopt-Heat: An economic optimization model to identify robust bioenergy technologies for the German heat transition.

Jordan, M., Millinger, M. and Thrän, D.

Submitted to SoftwareX

Benopt-Heat: An economic optimization model to identify robust bioenergy technologies for the German heat transition

Matthias Jordan[a,c,*], Markus Millinger[a], Daniela Thrän[a,b,c]

[a] *Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany*
[b] *DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Strasse 116, 04347 Leipzig, Germany*
[c] *University Leipzig, Institute for Infrastructure and Resources Management, Grimmaische Str. 12, 04109 Leipzig, Germany*

Abstract

Several energy system optimization models are used to identify solutions for the German energy transition. Most of them lack of detail in regard to the representation of the heterogeneous heat sector and the manifold bioenergy options. Benopt-Heat closes the gap and several research questions related to the future use of bioenergy in the German heat sector could be addressed. Based on the model results and novel methods to address uncertainty, policy insights with a high level of detail and confidence are generated. This software publication provides a basis to further investigate the manifold identified research questions in this field.

Keywords: Optimization, Heat sector, Bioenergy, Uncertainty assessment

Required Metadata

Current code version

Nr.	Code metadata description	
C1	Current code version	v1.0
C2	Permanent link to code/repository used for this code version	https://git.ufz.de/martinm/benopt-heat
C3	Code Ocean compute capsule	
C4	Legal Code License	GNU GPLv3
C5	Code versioning system used	git
C6	Software code languages, tools, and services used	Matlab, GAMS
C7	Compilation requirements, operating environments & dependencies	Window 7 or higher
C8	If available Link to developer documentation/manual	Wiki page of the git repository
C9	Support email for questions	matthias.jordan@ufz.de

Table 1: Code metadata

*Corresponding author
Email address: `matthias.jordan@ufz.de` (Matthias Jordan)

1. Motivation and significance

Climate change mitigation requires the heat sector to become almost carbon neutral by 2050, according to latest policy adjustments even by 2045. In Germany, the heat sector accounts for over 50 % of the final energy demand [4]. Nevertheless, the heat transition has stagnated in the last ten years and only 14,5 % of the heat supply is renewable today [26]. Energy system optimization models (ESOM) are widely used to identify cost optimal energy systems or transformation pathways to reach emissions targets. Several ESOMs were developed to investigate the German energy transition in general [8, 12, 21–24]. A review by Merkel et al. [15] identified that most of them lack of detail regarding the representation of the heterogeneous heat sector and data on biomass is in most cases highly aggregated. However, a detailed model including both the representation of the heterogeneous heat sector and the variety of possible bioenergy options has not been developed for Germany so far. Biomass contributes 86% of the renewable energy in the German heat sector today [1]. However, this resource from residues and energy crops is limited and almost completely exploited [3].

Applying existing models on the outlined research gap was evaluated to be not purposeful, as the complexity of the heterogeneous heat-sector and its possible supply concepts would require substantial modifications in the model structure. Consequently, Benopt-Heat was developed. In the model, the main heat sectors, private household, industry and trade/ commerce, are further divided into 19 sub-sectors, with different properties in terms of heat demand profiles, infrastructures and insulation standards. For each sub-sector, a variety of representative bioenergy-, fossil- and other renewable (hybrid-) heat technology concepts are described [13]. A detailed depiction of possible biomass products, their prices and their available potential is defined to assess the future cost-optimal biomass utilization. The model is embedded in a scenario frame, derived from long term energy transition scenarios describing the German energy transition from today to a strongly emission reduced energy system in 2050, e.g. [8, 23].

In addition, various issues that are related to ESOM projections are tackled with this model. One issue is related to the heterogeneity of stakeholders and consumers in the heat sector. Different interests, conditions and preferences are in place, influencing future market development beyond pure economically rational behavior. Integrating consumer heterogeneity and behavioral factors into ESOMs may generate new insights for energy policy.

Furthermore, uncertainties are one of the major challenges of ESOMs. The future transition of the energy system is shaped by a combination of factors that are deeply uncertain, as e.g. future energy price developments. A systematic assessment can identify which parameters drive the model output, test the robustness of the model results and help focus scenario analyses [5]. However, little use is made of these methods in ESOM-based analyses today.

Considering the above, the following research questions were assessed with Benopt-Heat:

- Which bioenergy technology concepts are competitive options in a future, climate target fulfilling heat sector and how does their potential role differ in different heat sub-sectors?

- Which uncertain factors have a significant influence on the future role of heat from biomass and which technology concepts are robust solutions based on these factors?
- How does the consideration of consumer choice affect optimal developments in different scenarios?

Based on the results from Benopt-Heat, future competitive bioenergy technologies were identified in several scenario analyses [6, 9]. A novel method was introduced combining the model with the variance based global sensitivity analysis of Sobol' and led to the identification of influential factors and robust bioenergy technologies under the investigated uncertain developments [10]. The introduced method delivers a valuable contribution to handle uncertainty in ESOMs and can serve as a case study for other researchers. Finally, for the first time, consumer heterogeneity and behavioral factors influencing investment decisions beyond cost minimization were integrated into an ESOM for the German heat sector [11]. The integration of consumer choice improves the behavioral realism of ESOMs and avoids using hurdle rates, growth rates etc. to smooth out projections and helps to understand the barriers that exist for new technologies. In summary, policy insights in regard to the future use of bioenergy in the German heat sector can be generated with a high level of detail and confidence, also considering future uncertainties and consumer behavior.

Benopt-Heat comes with an user interface, allowing to run customizable scenarios. The code is executed in a MATLAB environment coupled with GAMS.

2. Software description

2.1. Software Architecture

For the assessment of the outlined research questions a model of the German heat sector was developed using a mathematical optimization approach. As a programming environment GAMS [7] is used in combination with MATLAB [25]. In MATLAB the input data is imported from Microsoft EXCEL [16], edited and automatically sent to GAMS. The results from the optimizer are exported back to MATLAB, where they are evaluated and graphically prepared. The model is fully deterministic and uses perfect foresight. It is a linear model, using the Cplex solver. The spatial boundary is Germany as a whole. The technology and feedstock allocation is cost-optimized between today and 2050 in a yearly resolution. In the model nominal prices apply in $€_{2015}$. The approach of the model follows Benopt (BioENergyOPTimisation model), which was originally developed for biofuels assessments in the transport sector [18–20].

Fig. 1 shows the model architecture. The model consists of a user interface and six main modules (five MATLAB functions and the optimization module in GAMS). The six functions can be called from different applications such as the user interface or customizable scripts. The central function *Main.m* defines the sets and calls the functions of the model. The function *xlsx2mat.m* is handling the data import from EXCEL files and stores all input

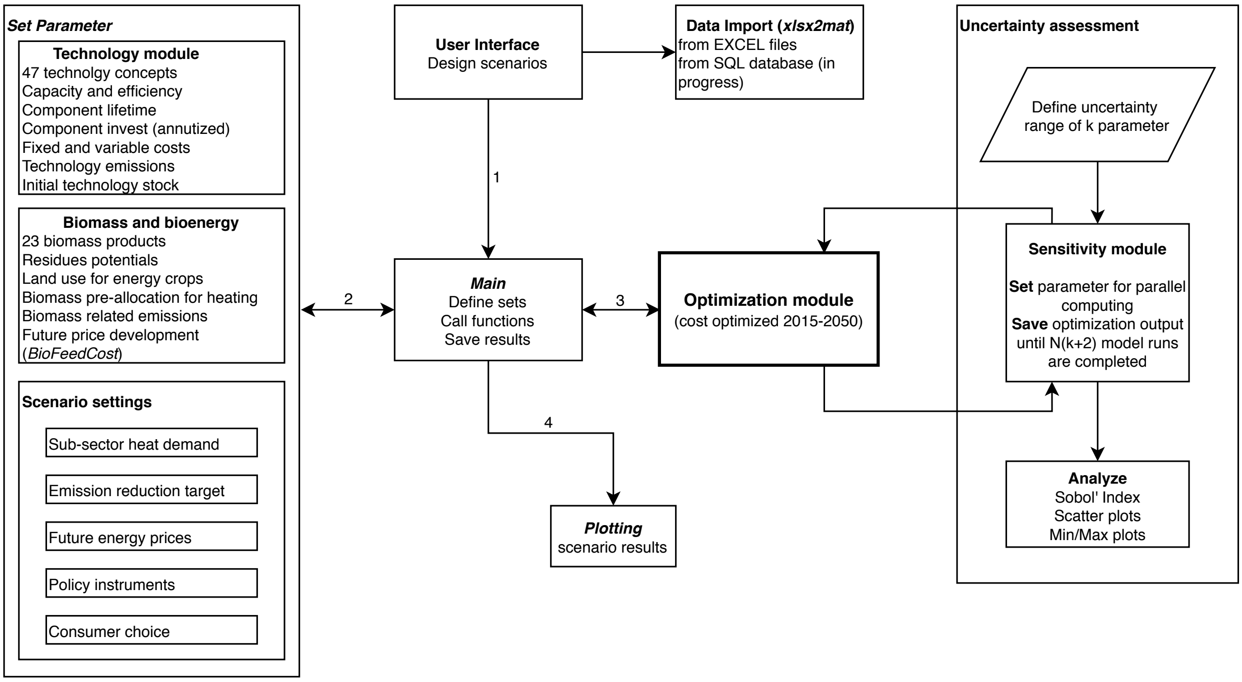

Figure 1: Model architecture schematic. Boxes represent modules and arrows represent data flow. The function names are written in italics. The optimization module is built in GAMS, all the other modules are built in MATLAB. The numbers on the arrow show the order in which the functions are executed. Data is imported from Excel files and all input parameters are stored in .mat files.

parameters in .mat files, which leads to a highly improved computing time when e.g. running a sensitivity analysis. Imported data is processed in the *SetParameter.m* function according to the selected scenario setting and is formatted to suit the data format required for the optimization in GAMS. Within the *SetParameter.m* function separate sections are defined for each parameter for clarity. Within this function *BioFeedCost.m* is called, a function calculating future biomass price developments. After the processing of all parameters, GAMS is called and the required parameters are sent to GAMS for the actual optimization using the GDXMRW data exchange protocol interfacing GAMS and MATLAB. The results from the GAMS optimization are sent back to MATLAB. Finally, a variety of scenario plots can be generated calling the *Plotting.m* function. Again, different plots are separated in sections for clarity within the function. Optimization results can be plotted directly at the end of the model run or from earlier saved results, which can be loaded via the user interface.

Users configure the model using the user interface for scenario calculations or adapt the scripts for sensitivity analysis. Additional functionalities, especially in relation to the Sobol' sensitivity analysis, can be executed using scripts. Due to its modular structure, the model can easily be adapted to new scenario data, extended with new technology concepts or new details on biomass feedstocks. A transfer to another country with different infrastructures and potential for renewable energy, on the other hand, could be a challenge and needs to be evaluated case by case.

2.2. *Software Functionalities*

User interface. Customizable scenarios can be designed and executed for predefined parameter values with the model user interface. The user can choose between predefined parameter values, which are shown in Fig. 2. The scenario calculations can be executed and optionally be saved. A variety of model output and input can be plotted, according to the user selection. Updated input data in the EXCEL files can be loaded into the model via the user interface.

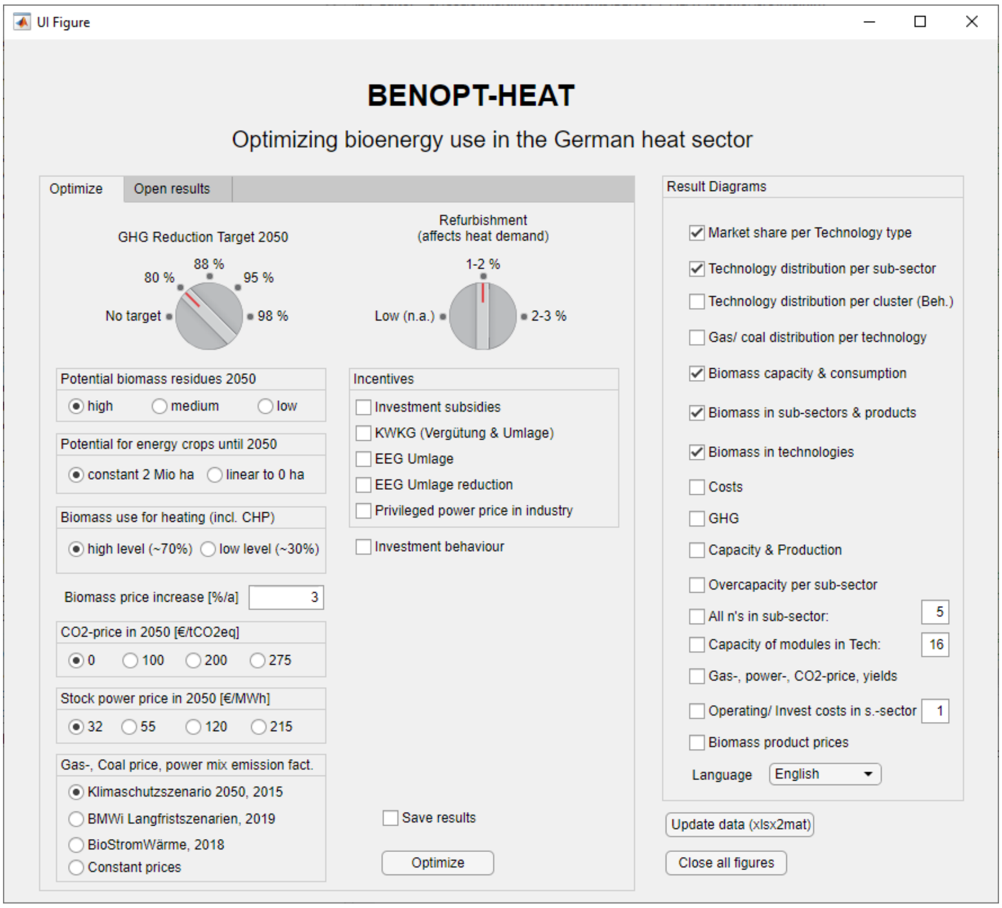

Figure 2: Model user interface.

Sub-sectors and technological options. The three main sectors of the German heat sector, private household, industry and trade/ commerce are further divided into 19 sub-sectors, with different properties in terms of heat demand profiles, infrastructures and insulation standards. The future development of the heat demand within the building sub-sectors is based on the results of the building stock model 'B-STar' [12], which models the future refurbishment of the German building stock in a yearly resolution. For each sub-sector, representative bioenergy-, fossil- and other renewable (hybrid-) heat technology concepts are described [13], incl. e.g. gas boiler, heat pumps, direct electric heating, solar thermal, log wood, wood pellet and wood chip technologies. Each (hybrid-)heat-technology concept is separated into different modules, defined by its capacity within the concept, the degree of efficiency, lifetime and investment costs. For each technology module investment costs, variable costs and the specific emissions are considered. For a detailed description of the implementation of the technologies into the sub-sectors see Section 2.1 in Jordan et al. [9].

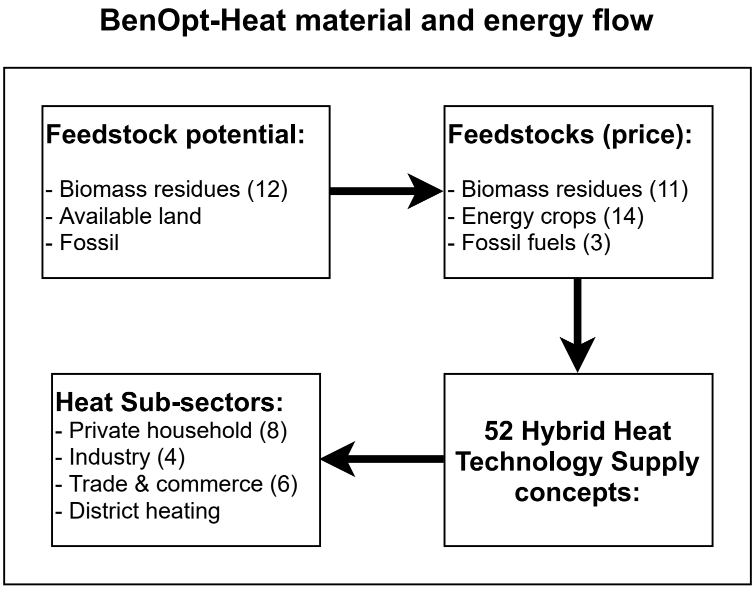

Figure 3: Model material and energy flow for the considered feedstocks. Arrows represent a matrix defining the possible pathways. Some feedstock potentials flow into one feedstock (price) category, some can flow in multiple categories.

Biomass and bioenergy. In total 25 biomass products (incl. wood based residues, log wood, straw, manure, two perennial crops and seven types of energy crops) and three fossil feedstocks are possible inputs for the model technologies [13]. The national potential for biomass residues is derived from the upper and lower range of the current energetic use and the exploitable potential described in Brosowski et al. [3], [2]. The cultivation of available land for energy crops is optimized within the model, limited by maximally doubling the land use per year for each type of energy crop. Biomass imports and exports are not considered as the analyses aim on the optimal allocation of the national biomass potential within Germany. From the overall available biomass potential (residues and energy crops), a user defined share is pre-allocated to the heat sector (incl. CHP applications). The model is free to pick from any category of residues and is free to cultivate any of the defined energy crops, as long as the defined upper scenario limit is not violated. The actual biomass usage from today serves as a starting point. Future biomass prices are projected using a method described in Millinger and Thrän [17], which was directly integrated into the model code and processes the yearly biomass price increase defined in the user interface.

Power sector interface. In the future, the heat sector is expected to be strongly linked to the power sector, due to the expected increase of power based heating systems as heat pumps and the use of CHP systems. Table 2 shows how consumed power for heating and power from CHP systems is priced and how emissions are allocated in the model. Additionally, in the different heat sub-sectors in Germany, final consumer prices for electricity vary. This is driven by varying charges in relation to the several components of the power price (e.g. taxes and levies). Consequently, these components are treated separately in the model and their future development is set according to projected trends. In the model, it is assumed that the power sector will be almost completely decarbonised by 2050.

Power	Price	Credit	Heat sector emissions
external demand	Final consumer price	0	Emissions from grid power mix
internally used for heating	0	0	Emissions from techn. system
internally used for non heating	0	Final consumer price	0
fed into the grid	0	Stock market price	0

Table 2: Model interface to the power sector in terms of power consumed for heating and power use of CHP / PV technologies. The emissions from grid-based electricity are allocated to the heat sector in accordance to the power mix specific emission factor.

Scenario settings. Within the model, a variety of parameters can be modified for a scenario setting. The user interface is a convenient tool for this purpose, delivering for each parameter a value (development) range derived from literature studies. Possible parameter modifications are: the setting of a GHG reduction target, the refurbishment rate affecting the heat demand, data related to the biomass potential, future energy price developments, policy incentives and the consideration of consumer behavior. For the consideration of consumer behavior related to heating system investment decisions, empirical data on consumer choice for adopting residential heating systems was identified in the literature. This data was integrated into the model, combining established methods for integrating consumer heterogeneity and a novel approach for calculating indirect costs, representing behavioral factors [11].

Plotting. Based on the scenario results, a variety of figures can be generated according to the selection of the user. Different plots are available on the technology and feedstock market shares on different levels, especially in regard to the biomass and bioenergy use. The resulting distribution of costs and emissions and some input parameters as energy prices and operating costs can be shown. Additionally, plots in regard to the capacity and the number of heating systems installed/ invested in/ decommissioned etc. can be plotted for verification of the model functionality. Various annotated scripts are available for the presentation of the results in relation to the sensitivity analysis, which can be individually adapted (e.g. Sobol' indices, scatter plots).

Uncertainty assessment. A detailed illustration of how the variance based sensitivity analysis of Sobol' is applied to the model and how further analyses can be conducted is shown in Jordan et al. [10]. After the user defined a uncertainty range for selected parameters, Sobol' indices are calculated, quantifying the impact of uncertain input parameters on the predefined model output. The Sobol' indices range from 0..1 and quantify the main impact of the parameter and the impact of the parameter in interaction with all other parameters. For the execution of the implemented sensitivity analysis of Sobol', parallel computing is recommended to overcome the computational burden, as e.g. implemented in Jordan et al. [10]. Based on the Sobol' indices, further analyses can be conducted, e.g. by the generation of scatter plots.

3. Illustrative Examples

Exemplary, an extreme scenario is calculated for this paper: the GHG reduction target in the heat sector is set to 98% compared to 1990, a strongly increasing CO_2 price and a high refurbishment rate are set. Additionally, a high biomass potential is available and pre-allocated to the heat sector and energy prices are kept constant. Policy incentives are not in place and consumer choice is not considered. The scenario was designed by customizing the parameters within the user interface. Within the model, a cost-optimal transformation pathway from 2015 until 2050 is calculated while fulfilling the heat demand and the GHG reduction target as a restriction.

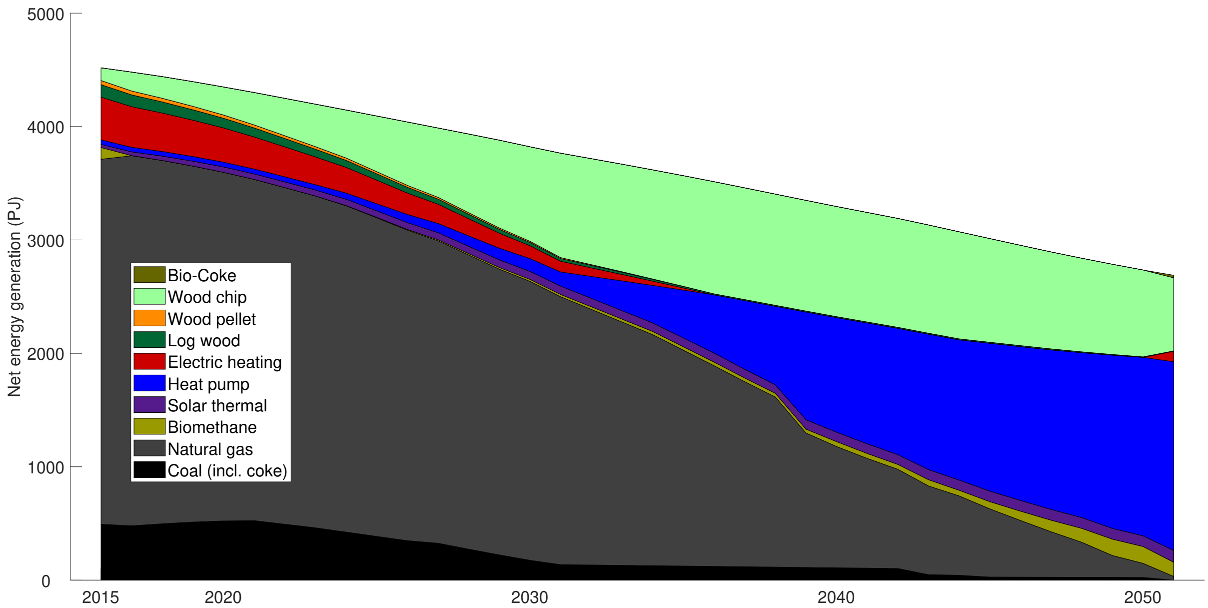

Figure 4: Model resulting development of the technology market shares for the complete heat sector in a yearly resolution.

The resulting development of the technology market shares are shown for the complete heat sector in Fig. 4. The technology shares of the ten technology types are summarized over all technological (hybrid) concepts. The figure shows that a mostly fossil based heat supply in 2015 is continuously replaced by renewable technology options. Beside heat pumps, bioenergy technologies using wood chips are especially competitive options and gain major market shares.

In the top of Fig. 5, the overall available biomass potential from residues in the eleven predefined categories is shown. In the middle graph of Fig. 5, the actual used biomass is presented and the lower graph shows the available land for the cultivation of energy crops and the actual amount of cultivated land, internally determined by the model. The results show that in the first 20 years not all the available biomass is used in the model. However, over time biomass becomes more competitive and the yearly potential is exploited, which is mainly driven by an increasing GHG reduction target and increased emissions pricing. Additionally, the results show that particularly solid, wood based biomass is a competitive option. However, from 2030 onwards digestible biomass becomes an additional competitive option to fulfill the climate targets.

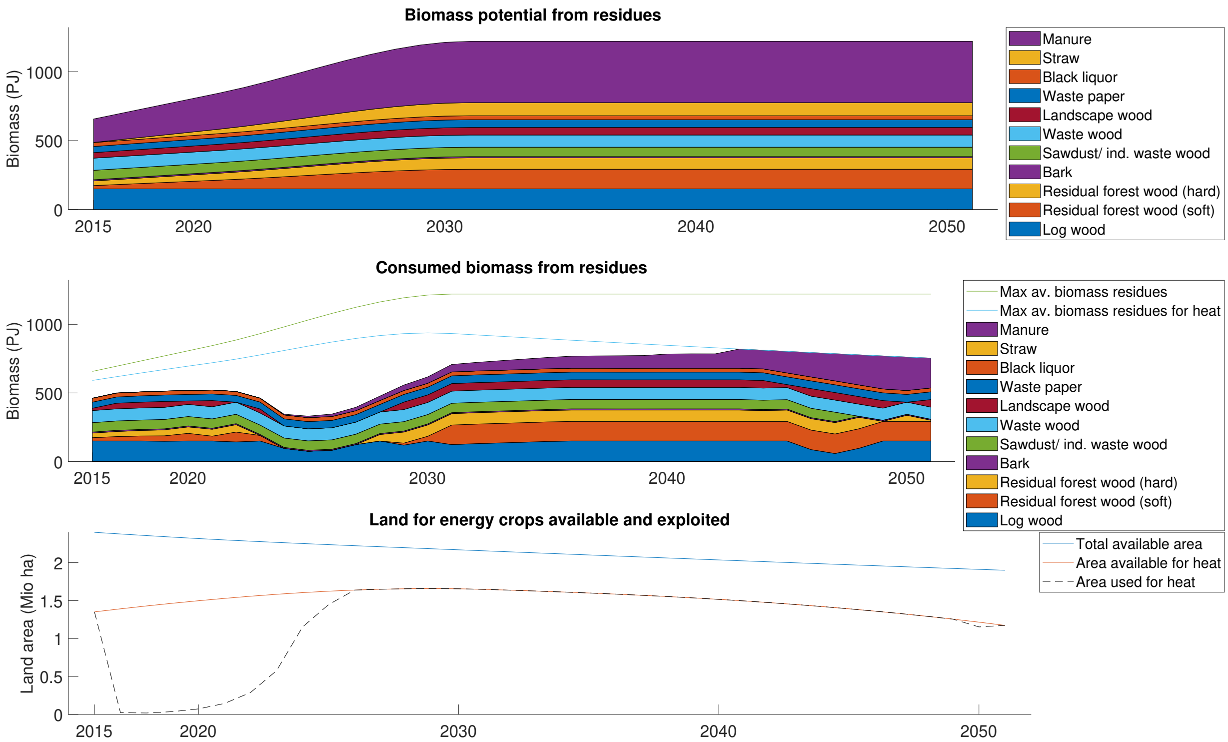

Figure 5: Available and consumed biomass potential in a yearly resolution.

With this example, the major functions for a scenario calculation are shown. However, an uncertainty assessment was not conducted for this paper. For a comprehensive example of how the sensitivity analysis is conducted, the reader is referred to Jordan et al. [10].

4. Impact

In addition to the several ESOMs that exist for modeling the energy transition in Germany, but which are lacking in detail with regard to the heat sector and the representation of bioenergy, Benopt-Heat is introduced, which addresses both deficits. The model includes a detailed representation of the heterogeneous heat sector and a variety of possible bioenergy feedstock and technological options. The model was applied in several studies delivering policy insights in regard to the future role of bioenergy within the German heat transition.

These policy insights come with a high level of detail and confidence, since future uncertainties are thoroughly investigated and consumer heterogeneity and investment behavior are considered. For example, competitive bioenergy technologies in the German heat sector were identified in several scenarios for the Federal Ministry of Economic Affairs and Energy (BMWi) [6, 9]. In addition to this study, robust bioenergy technologies for the German heat transition under uncertain developments of 32 input factors were presented in a solution space by applying a comprehensive sensitivity analysis, which additionally identified significant influential parameters on the future competitiveness of bioenergy [10]. Further, the effect of applying consumer investment behavior on the future bioenergy market development within the model was investigated [11]. Moreover, the model contributed to a study identifying solutions for a CO_2-free heat supply in private households [27].

The outlined investigations led to the identification of further research questions. For instance, it was identified that biomass is particularly competitive in the industry sector, but the data basis for these sub-sectors lacks detail. For more detailed insights, regarding the specific applications into which biomass can be competitively distributed in the industry, further research in this direction is highly recommended from the authors' view. This issue is comprehensively discussed in Lenz et al. [14]. Moreover, it is found that the methodological and the data basis for integrating consumer choice into the model is limited. For future research, more recent and detailed empirical data and methodological progress, as e.g. a model calibration would be desirable.

In addition, the model is and will be used to evaluate the future competitiveness of newly developed bioenergy heat technologies, designed at the German biomass research center (DBFZ). Plans also include the fusion of the model with another ESOM optimizing the bioenergy use in the German transport and electricity sector [19]. Finally, investigating the effects of an increased temporal resolution seems worthwhile, since the heat demand, solar thermal yield etc. varies seasonally. However, with an increased temporal resolution, resulting in a longer model run-time, the possibility to apply a comprehensive sensitivity analysis is reduced.

5. Conclusions

With the presented model the outlined research gap could be addressed. The possible future role of biomass in the German heat transition was assessed in a high level of detail in regard to the representation of the heat sector and the possible (hybrid) bioenergy technology concepts. Future competitive bioenergy technologies and their corresponding feedstocks could be identified with the model considering a variety of future uncertainties and the influence of consumer choice. Additionally, significantly influential factors on the future competitiveness of bioenergy had been identified to show the interdependencies for policymakers. With the outlined uncertainty assessment, policy insights could be delivered with a high level of confidence.

6. Conflict of Interest

No conflict of interest exists: We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

This work was funded by the Bundesministerium für Wirtschaft und Energie (03KB113B) and the Helmholtz Association of German Research Centers and supported by Helmholtz Impulse and Networking Fund through Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE).

Thank you to Öko-Institut e.V. for sharing the heat demand data calculated with B-STar (Building Stock Transformation Model), which were used in this study for the defined household, trade and commerce and district heating markets [12].

Thank you to Volker Lenz for providing technical and economic technology data on which this and former studies are build on.

References

[1] Development of Renewable Energy Sources in Germany in the year 2020. URL https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/development-of-renewable-energy-sources-in-germany-2020.pdf?__blob=publicationFile&v=29.

[2] DBFZ - Data repository: Ressource database (Ressourcendatenbank), 2019. URL http://webapp.dbfz.de/resources.

[3] André Brosowski, Tim Krause, Udo Mantau, Bernd Mahro, Anja Noke, Felix Richter, Thomas Raussen, Roland Bischof, Thomas Hering, Christian Blanke, Paul Müller, and Daniela Thrän. How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany. *Biomass and Bioenergy*, 127:105275, 2019. ISSN 09619534. doi: 10.1016/j.biombioe.2019.105275.

[4] Bundesministerium für Wirtschaft und Energie. Energy data (Energiedaten): Complete edition (Gesamtausgabe). URL https://www.bmwi.de/Redaktion/DE/Downloads/Energiedaten/energiedaten-gesamt-pdf-grafiken.pdf?__blob=publicationFile&v=40.

[5] Joseph DeCarolis, Hannah Daly, Paul Dodds, Ilkka Keppo, Francis Li, Will McDowall, Steve Pye, Neil Strachan, Evelina Trutnevyte, Will Usher, Matthew Winning, Sonia Yeh, and Marianne Zeyringer. Formalizing best practice for energy system optimization modelling. *Applied Energy*, 194:184–198, 2017. doi: 10.1016/j.apenergy.2017.03.001.

[6] ETA-Florence Renewable Energies, editor. *Competitive Biomass Key Applications to Fulfill Climate Targets in the German Heat Sector: Findings from Optimization Modelling*, 2019. ETA-Florence Renewable Energies. doi: 10.5071/27thEUBCE2019-5BV.3.10. URL http://www.etaflorence.it/proceedings/?detail=16385.

[7] GAMS Development Corp. GAMS, 2019. URL https://www.gams.com/.

[8] Philipp Gerbert, Patrick Herhold, Jens Burchardt, Stefan Schönberger, Florian Rechenmacher, Almut Kirchner, Andreas Kemmler, and Marco Wünsch. Klimapfade für Deutschland. URL https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2018/Januar/Klimapfade_fuer_Deutschland_BDI-Studie_/Klimapfade-fuer-Deutschland-BDI-Studie-12-01-2018.pdf.

[9] Matthias Jordan, Volker Lenz, Markus Millinger, Katja Oehmichen, and Daniela Thrän. Future competitive bioenergy technologies in the German heat sector: Findings from an economic optimization approach. *Energy*, 189:116194, 2019. ISSN 03605442. doi: 10.1016/j.energy.2019.116194.

[10] Matthias Jordan, Markus Millinger, and Daniela Thrän. Robust bioenergy technologies for the German heat transition: A novel approach combining optimization modeling with Sobol' sensitivity analysis. *Applied Energy*, 262:114534, 2020. doi: 10.1016/j.apenergy.2020.114534.

[11] Matthias Jordan, Charlotte Hopfe, Markus Millinger, Julian Rode, and Daniela Thrän. Incorporating consumer choice into an optimization model for the German heat sector: Effects on projected bioenergy use. *Journal of Cleaner Production*, 295(5):126319, 2021. ISSN 09596526. doi: 10.1016/j.jclepro.2021.126319.

[12] Matthias Koch, Klaus Hennenberg, Katja Hünecke, Markus Haller, and Tilman Hesse. Role of bioenergy in the electricity and heating market until 2050, taking into account the future building stock (Rolle der Bioenergie im Strom- und Wärmemarkt bis 2050 unter Einbeziehung des zukünftigen Gebäudebestandes). URL `https://www.energetische-biomassenutzung.de/fileadmin/Steckbriefe/dokumente/03KB114_Bericht_Bio-Strom-W%C3%A4rme.pdf`.

[13] Volker Lenz and Matthias Jordan. Technical and economic data of renewable heat supply systems for different heat sub-sectors., 2019. URL `http://dx.doi.org/10.17632/v2c93n28rj.2`.

[14] Volker Lenz, Nora Szarka, Matthias Jordan, and Daniela Thrän. Status and Perspectives of Biomass Use for Industrial Process Heat for Industrialized Countries. *Chemical Engineering & Technology*, 133(5):57, 2020. ISSN 09307516. doi: 10.1002/ceat.202000077. URL `https://www.fvee.de/fileadmin/publikationen/Themenhefte/th2019/th2019.pdf`.

[15] Erik Merkel, Russell McKenna, Daniel Fehrenbach, and Wolf Fichtner. A model-based assessment of climate and energy targets for the German residential heat system. *Journal of Cleaner Production*, 142:3151–3173, 2017. ISSN 09596526. doi: 10.1016/j.jclepro.2016.10.153.

[16] Microsoft. Microsoft Excel, 2019. URL `https://products.office.com/de-de/excel`.

[17] M. Millinger and D. Thrän. Biomass price developments inhibit biofuel investments and research in Germany: The crucial future role of high yields. *Journal of Cleaner Production*, 172:1654–1663, 2016. ISSN 09596526. doi: 10.1016/j.jclepro.2016.11.175.

[18] M. Millinger, K. Meisel, and D. Thrän. Greenhouse gas abatement optimal deployment of biofuels from crops in Germany. *Transportation Research Part D: Transport and Environment*, 69:265–275, 2019. ISSN 13619209. doi: 10.1016/j.trd.2019.02.005.

[19] Markus Millinger. BioENergyOPTimisation model, 2019. URL `10.5281/zenodo.2812986`.

[20] Markus Millinger, Kathleen Meisel, Maik Budzinski, and Daniela Thrän. Relative Greenhouse Gas Abatement Cost Competitiveness of Biofuels in Germany. *Energies*, 11(3):615, 2018. ISSN 1996-1073. doi: 10.3390/en11030615.

[21] Joachim Nitsch, Thomas Pregger, Tobias Naegler, Dominik Heide, Diego Luca de Tena, Franz Trieb, Yvonne Scholz, Kristina Nienhaus, Norman Gerhardt, Michael Sterner, and Tobias Trost. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global: Schlussbericht. URL `http://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf`.

[22] Benjamin Pfluger, Bernd Tersteegen, and Bernd Franke. Langfristszenarien für die Transformation des Energiesystems in Deutschland: Modul 3: Referenzszenario und Basisszenario Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie. URL `https://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-3-referenzszenario-und-basisszenario.pdf?__blob=publicationFile&v=4`.

[23] Julia Repenning, Lukas Emele, Ruth Blanck, Hannes Böttcher, Günter Dehoust, Hannah Förster, Benjamin Greiner, Ralph Harthan, Klaus Hennenberg, Hauke Hermann, Wolfram Jörß, Charlotte Loreck, Sylvia Ludig, Felix Matthes, Margarethe Scheffler, Katja Schumacher, Kirsten Wiegmann, Carina Zell-Ziegler, Sibylle Braungardt, Wolfgang Eichhammer, Rainer Elsland, Tobais Fleiter, Johannes Hartwig, Judit Kockat, Ben Pfluger, Wolfgang Schade, Barbara Schlomann, Frank Sensfuß, and Hans-Joachim Ziesing. Climate protection scenario 2050 (Klimaschutzszenario 2050): 2. Endbericht -

Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit. URL `https://www.oeko.de/oekodoc/2451/2015-608-de.pdf`.

[24] Michael Schlesinger, Dietmar Lindenberger, and Christian Lutz. Entwicklung der Energiemärkte - Energiereferenzprognose: Projekt Nr. 57/12 Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie. URL `https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht.pdf?__blob=publicationFile&v=7`.

[25] The MathWorks Inc. MATLAB, 2019. URL `https://de.mathworks.com/products/matlab.html`.

[26] Umweltbundesamt. Renewable energies in germany (Erneuerbare Energien in Deutschland): Data on development in 2019 (Daten zur Entwicklung im Jahr 2019). URL `https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-04-03_hgp-ee-in-zahlen_bf.pdf`.

[27] Bernhard Wern, Volker Lenz, Evelyn Sperber, Ali Saadat, Dietrich Schmidt, Peter Engelmann, Dominik Hering, Andre Xhonneux, Federico Giovanetti, Ferdinand Schmidt, Matthias Jordan, Sebastian Strunz, and Hans-Peter Ebert. Wärmebereitstellung in Privathauhalten - Lösungen für eine CO2-freie Energiebereitstellung. In FVEE-Themen, editor, *Energy Research for Future: Beiträge zur FVEE-Jahrestagung 2019*, pages 28–32, 2019.

ISSN 1860-0387

Helmholtz Centre for
Environmental Research – UFZ
Permoserstraße 15
04318 Leipzig I Germany
www.ufz.de

NOT FOR SALE.