Renewable and Sustainable Energy Transition 2 (2022) 100028

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Transition

journal homepage: www.journals.elsevier.com/renewable-and-sustainable-energy-transition

The potential of behavioral changes to achieve a fully renewable energy system - A case study for Germany

M.H. Eerma [a,1], D. Manning [a,b,1], G.L. Økland [a,b,1], C. Rodriguez del Angel [a,1], P.E. Seifert [a,b,1], J. Winkler [a,1], A. Zamora Blaumann [a,1], E. Zozmann [a,1,*], S.S. Hosseinioun [a,2], L. Göke [a,c], M. Kendziorski [a,c], C. Von Hirschhausen [a,c]

[a] *Technical University of Berlin, Berlin 10623, Germany*
[b] *Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*
[c] *German Institute for Economic Research (DIW Berlin), Berlin 10117, Germany*

ARTICLE INFO

Keywords:
Behavioral changes
Energy system modeling
Demand-side solutions

ABSTRACT

The paper provides energy system-wide estimates of the potential and impacts of final energy demand reductions based on behavioral changes in different sectors. Behavioral changes are for example adjusting thermostats or replacing business flights with telemeetings. By reducing demand, behavioral changes are a potentially decisive but seldomly considered factor to support the transformation towards a decarbonized energy system. Therefore, this paper addresses the following question: What is the potential of behavioral changes and what are the impacts on the supply side of a 100% renewable energy system? For this purpose, an extensive literature review is conducted to obtain estimates for the effects of different behavioral changes on final energy demand in Germany. The impact of these changes on the supply side and system costs is quantified using a bottom-up planning model of a renewable energy system. Results indicate that final energy could be reduced by up to 20.5% and as a result, renewable capacity reductions between 13.6% to 30.6% are conceivable. The greatest potential for behavioral changes was identified in the heating sector.

1. Introduction

Since the Paris Agreement in 2015, annual CO_2 emissions have increased by more than 4% and the remaining emission budget to stay within 1.5° C of global warming is shrinking rapidly [1,2]. There is an extensive and growing variety of studies on how to decarbonize energy supply that focuses on technological options, for example renewable energies, nuclear power and carbon capture, transport and storage. However, in consumption-based accounting approximately two thirds of global emissions are linked to private households and apart from increasing energy efficiency, little effort is made to reduce final energy demand [3–5]. Despite this high potential for climate change mitigation, demand side solutions are still poorly understood and previous work has found that these are still insufficiently covered by quantitative energy system models [2,3]. Against this background, this study evaluates the impact of behavioral changes in an energy system based on 100% renewable energy.

Absolute reductions in final energy demand based on behavioral changes are often linked to the concept of *energy sufficiency*. While there is no universal definition of energy sufficiency, a recently published paper finds that definitions are more and more associated with "the strategy of achieving absolute reductions of the amount of energy-based services consumed, notably through promoting intrinsically low-energy activities, to reach a level of enoughness that ensures sustainability" [6]. The demand reductions identified in this paper are associated with this concept, but without explicitly quantifying a level of enoughness. Instead of sufficiency, the term *behavioral changes* is therefore used. Behavioral changes are henceforth understood as reductions in final energy demand based on lifestyle changes, for example by lowering thermostats or replacing business flights with telemeetings.

Abbreviations: TWh, Terawatt hours; GW, Gigawatt.

[*] Corresponding author.

E-mail address: elmarzozmann@posteo.de (E. Zozmann).

[1] These authors contributed equally to this work.

[2] These authors contributed to the original research.

https://doi.org/10.1016/j.rset.2022.100028
Received 20 January 2022; Received in revised form 5 July 2022; Accepted 11 July 2022

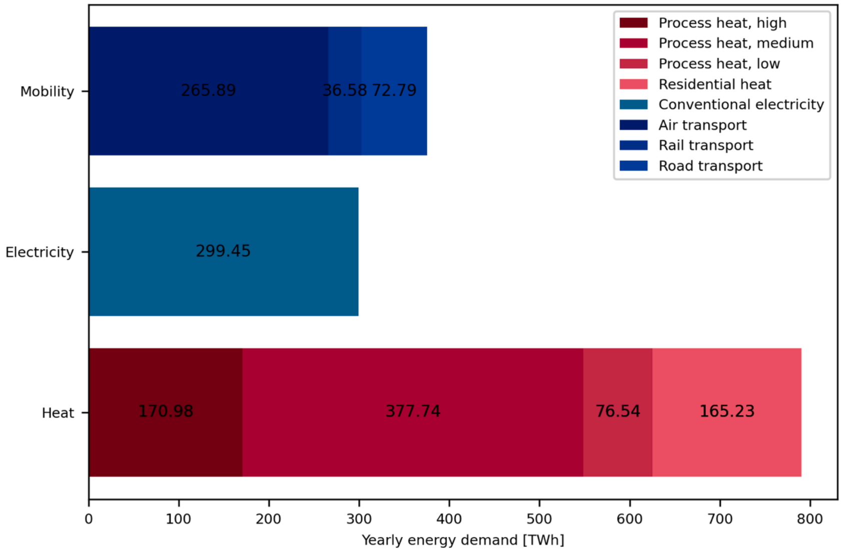

Fig. 1. Annual energy demand 2050 in terawatt hours [TWh] by sector. Color shade and black numbers represent the subcategories of the respective data. Own illustration based on Auer et al. [23].

Understanding and quantifying the potential of behavioral changes for decarbonising the energy system can identify key leverages and increase the likelihood of utilising this potential. A large and growing body of literature exists that describes approaches, potentials and policies for promoting behavioral changes that reduce absolute energy demand [6–10]. While these studies demonstrate opportunities for behavioral changes, Toulouse et al. [11] indicate that incorporating such measures in energy system modelling and defining quantitative scenarios for it is necessary to provide objective criteria for policy-makers. So far, most quantitative energy system studies have not been including behavioral changes and the associated demand reduction potential [4,12,13].

For Germany, there are several studies that model a decarbonized energy system in 2050. A study published in 2018 found that from 11 scenarios in the reviewed studies, only 3 scenarios explicitly incorporated and described the potential of behavioral changes, namely the *KS 95* scenario [14] and the scenarios *GreenLife* and *GreenSupreme* [15]. In a more recent publication, a scenario called *Sufficiency* explicitly models a decreasing energy demand based on behavioral changes [16]. The few studies that include behavioral changes find that a more environmentally conscious behavior could substantially reduce cost and renewable capacities [15,16]. However, a large body of policy-relevant studies in the same field does not consider behavioral changes at all or limits them to some assumptions in the mobility sector [17–20]. This paper seeks to fill this gap by explicitly describing and modeling the potential of demand reductions based on behavioral changes instead of including them only as a scenario. Based on an extensive literature review, the potential of behavioral changes for the heat, mobility and electricity sector is estimated. A cost minimizing bottom-up planning model is applied to estimate the impacts of these reductions on the supply side of a 100% renewable energy system in Germany. The model is implemented in the AnyMOD framework [21,22] with renewable availability time series in an hourly temporal resolution and technology cost assumptions for 2035.

This remainder of this paper is organized into six sections. The next section identifies the potential for behavioral changes for the heat, mobility, and electricity sector. Section 3 lays out the energy system model applied and introduces two scenarios with different levels of ambition regarding behavioral changes. Section 4 and Section 5 present and discusse the results, Section 6 concludes.

2. Quantifying the potential of behavioral changes

The potential for demand reductions based on behavioral changes for Germany in the heat, mobility, and electricity sector is quantified from existing literature. Each of the following subsections provides an overview on demand reduction potentials for one sector and concludes with an overall potential for the sector. Most of the demand reductions are only valid for a specific subset of energy demand, e.g. assuming a reduction in short-distance passenger flights only reduces the energy demand of private aviation. Fig. 1 gives an overview of the reference energy demand data used in this paper. The data is taken from the *openENTRANCE* project that develops scenarios compliant with the Paris Agreement [23]. The scenario “societal commitment” was chosen, which aims for a strong change of behavior towards a sustainable lifestyle. This scenario already includes energy demand reductions in transport and delivering services, combined with advantages of intense digitalization and first steps towards a circular economy. Given that the demand data is for 2050 and that it already assumes a certain bias towards a more sustainable lifestyle might influence the model results. However, this data was selected since it is one of the few open-source data sets that include time series for all sectors in a high temporal resolution. Furthermore, the focus of this paper lies on the impacts of behavior-based demand reductions, hence this drawback was considered to be negligible. Demand data from this project has also been cross-checked for consistency with other publications, most notably the *SET-NAV* project [23]. Demand data is differentiated in the sectors mobility, heat and electricity, which are further divided into subcategories (as shown in Fig. 1). The mobility sector uses electricity for road and rail transport and hydrogen for aviation. The heat sector includes electricity for residential heat and parts of process heat, synthetic gas in process heat, and hydrogen in low-temperature process heat. The potential for behavioral changes is quantified based on this data, meaning that the overall potentials at the end of each subsection are derived by linking the reductions from literature to the respective shares of energy demand. There are no assumptions on when the reductions occur, meaning that an equal proportion is deducted from every hour of the year. To account for variations in the scale of demand reductions, the potential also varies by ambition of behavioral changes, hereafter referred to as the *Low Ambition* and *High Ambition* scenario.

Table 1
Low and High Ambition reduction potential for residential/commercial and process heat energy demand.

Reduction potential	Residential/ commercial (20.9%)	Process heat low (9.7%)	Process heat mid (47.8%)	Process heat high (21.6%)	Total Heat
Low ambition	-5.0%	-8.6%	-5.1%	-3.0%	−5.0%
High ambition	-34.2%	-13.2%	-12.0%	-7.6%	−15.8%

2.1. Heat sector

With 54% of overall energy demand, the heat sector has significant importance for decarbonization. The sector is subdivided into residential-commercial and process heat demand, with the latter subdivided by temperature levels. The conceivable demand reductions are summarized in Table A3 in the Appendix. For the *Low Ambition* and *High Ambition* scenario the reduction potential is depicted in Table 1. Negative percentages refer to the reductions that are derived for the respective category based on literature, differentiated for the *Low Ambition* and *High Ambition* scenario. Percentages in the column headings refer to the share of total heat demand, e.g. residential/commercial accounts for approximately 21 percent of total heat energy demand.

2.1.1. Residential and commercial heat

The average room temperature for Germany's households is 19.6° C [37]. It is assumed that a reduction of 1° C is acceptable without diminishing the living comfort. The German Federal Environmental Agency finds a potential of 4.4% to 9% in 2030 by reducing the temperature by 1 or 2° C, taking into account the refurbishment rate in Germany [24]. A report from Cambridge Architectural Research estimates the energy saving potential of small changes in household behavior based on a building simulation. They identify a reduction potential of 13% of the space heating energy by turning down the thermostat by 1 ° C [26]. Marshall et al. [25] calculate energy savings considering four different measures for three different occupancy patterns. Energy savings of 9% are achievable by reducing the households' space temperature by 1° C.

Palmer et al. [26] argue that the installation of water-efficient shower heads can save up to half of the energy usage for showering. An additional change in behavior caused by climate awareness or price incentives can reduce energy demand for hot water by approximately 20–30%, as a consequence of shorter and less frequent showering. Toulouse and Attali [28] present an average cut of 5–10% in energy usage, which emerges from feedback about showering time. As stated by Lehmann et al. [29], the demand for hot water in households can be reduced through shortening the daily shower time and adjusting the water consumption with water-saving fittings by up to 70%.

Bierwirth and Thomas [27], 38] argue that the European trend of increasing living space per person creates high energy demand. Their analysis focuses on the balance between a sufficient floor space for a decent living. The average living space 2018 in Germany is 46.7m^2 per person [39]. Taking into account five different sizes of households, Bierwirth and Thomas [27] calculate an "adequate" average space of 32.3m^2 per person. Consequently, an energy saving potential of 24.9% based on 35m^2 per capita to 35.7% based on 30m^2 per capita is assumed to be reasonable for space heating. Associated reductions of energy service demand related to lighting and building material are not included and would lead to even more saving potentials. Compared to other European countries, the demand reduction potential of Germany is rated as very high and is only surpassed by Luxembourg [27].

2.1.2. Process heat

Demand reductions in the industry sector are for example when energy intensive materials are substituted by less energy intensive products [31]. Energy demand for process heat is subdivided by industry branch according to Auer et al. [23], which serves as the baseline demand shown in Table 2. It is assumed that each of the following demand reductions only affects its respective industry sector. Approximately 12% of total process heat demand relate to low-temperature heat; 60% to mid-temperature, and 27% to high-temperature. The following discusses demand reductions for process heat, with one paragraph per temperature level.

As shown in Table 2, the food industry accounts for almost 50% of the low-temperature demand. The current level of food waste could be reduced from 35% to 17.5% to reduce the energy demand of the food industry [30]. A more ambitious assumption of limiting food consumption to 2586 kcal per day leads to a energy demand reduction of 27% [31]. These behavioral changes translate to 8.6% and 13.2% reduction potential of low-temperature heat demand in *Low Ambition* and *High Ambition*, respectively.

While the recycling rate for plastics currently only amounts to 47%, the rate for paper and metal products is 75.9% and 92%, respectively [33,34]. Assuming that plastic recycling can reach similar recycling rates as paper and metal, mid-temperature heat demand can be reduced by 1.4% in *Low Ambition* and 2.1% in *High Ambition*. Another key strategy mentioned in many studies is an extended product lifetime [24, 40]. Implementing a statutory warranty of 5 years and setting the defects liability to 10 years could save at least 14.8% of the produced products. Additionally, regulating a mandatory availability of components for at least 20 years would ensure prospective repairability. Assuming a similar substitution quota for all product categories reduces the manufacturing and engineering energy demand by 14.8%, leading to an overall mid-temperature heat demand reduction of 3% [35]. Another potential to decrease energy demand through changed consumption patterns is by supporting consumption communities as an example of shared economies. Research carried out by Vita et al. [31] finds a consumption reduction of 50%, where 10% will be shifted to services. Accordingly, the remaining 40% can be attributed to behavioral changes, resulting in a demand reduction potential of 8.2% in mid-temperature heat.

Promoting a modal shift in the construction industry from steel and cement to wooden structures could significantly reduce industrial energy demand, as the iron and steel production makes up 86% of high-temperature heat demand. According to Hertwich et al. [36], 10% of all construction materials can be replaced by wood already. By assuming such replacement rates for steel in the construction industry, a demand reduction potential of 3% could be achieved. Based on a reduced average floor space per capita in the residential and commercial heating, as discussed in 2.1.1, a similar reduction in construction materials is assumed. This leads to a potential demand reduction of 4.6% in high-temperature heat demand due to reduced steel production and a potential demand reduction of 1% in mid-temperature heat demand due

Table 2
Process heat demand share of industry branches. Process heat is differentiated into low, mid and high temperature. Percentages refer to the shares of the industry branch on each temperature level [23].

Temperature	Food	Paper	Chemical	Engineering / Manufacturing	Refineries	Other	Non-metallic Minerals	Iron / Steel	Non-ferrous / Metals
Low < 100° C	49.0%	51.0%	0	0	0	0	0	0	0
Mid < 500 ° C	0	0	41.3%	20.6%	12.4%	12.3%	13.41%	0	0
High > 500 ° C	0	0	0	0	0	0	0	85.9%	14.1%

Table 3
Low and High Ambition reduction potential for air, road and rail mobility energy demand.

Reduction potential	Air (71%)	Road (19%)	Rail (10%)	Total Mobility
Low Ambition	-21.6%	-17.7%	-30.2%	-21.7%
High Ambition	-31.9%	-21.3%	-41.9%	-30.9%

to decreased cement production. For a more detailed description of the calculation process for process heat, see Zamora Blaumann et al. [41].

2.2. *Transport sector*

Despite increases in energy efficiency in the mobility sector, its energy consumption has been rising continuously since 2010 [42]. The German government committed to a reduction of final energy consumption in the mobility sector of 15% to 20% compared to 2005 levels to achieve reductions of 60% by 2050 in total energy demand. Data for mobility demand is divided in rail (19.4%), road (9.8%), and air (70.8%) transport, which is further separated in passenger and freight transport. While in this study rail and road technologies are expected to run with electricity only, air transport demand is fully met by hydrogen [23].

While there is a variety of narratives of a future mobility system, little research explicitly investigates absolute demand reductions. Fischer et al. [24] discusses four measures with regards to the transport sector: An increased usage of bicycles, replacing business trips with telemeetings, smaller passenger cars and a reduction of private aviation. Van de Ven et al. [43] model the potential impacts of behavioral changes on climate change mitigation, including several measures in the transport sector. A demand reduction of 30 and 55% in 2050 for motorized individual transport and aviation respectively is modeled by Sterchele et al. [44]. Two other studies examine the socio-technical transformation of the Danish transport sector, including changes induced by different human behavior [45,46]. Table A2 in the Appendix provides an overview of these measures. In the following, potential demand reductions for road, rail and aviation transport are discussed.

2.2.1. *Road*

Passenger cars are the strongest driver of energy demand in the non-commercial mobility sector. If shorter distances are covered with bicycles, the energy demand for cars could be reduced by up to 10% [24, 43]. According to the statistics published by the German Ministry of Transport, 18% of passenger car transport is due to commuting to work [47]. Assuming that only one day of home office is possible each week, transport demand related to commuting could be reduced by 20% [43]. A further 19% of passenger car transport is due to business travels [47]. Consequently, transport demand related to business travels could be reduced by 60%, assuming that business trips are gradually replaced by telemeetings [24]. Energy demand of passenger car transport is also influenced by the size of private vehicles. Regulations or a changed consumer preference towards smaller private vehicles could therefore potentially reduce this demand by 7.5%. Finally, more energy-efficient driving patterns could reduce the energy demand of cars by 5% [43]. While several studies that include some assumptions on behavioral changes in the mobility sector consider a modal shift from passenger cars to passenger rail transport [15–18,20], it is not considered in this analysis. This will be further discussed in Section 5.

The German government aims to reduce energy consumption of the total freight transport in Germany by up to 20% in 2030, which includes both road, rail and air freight transport [48]. Training on efficient driving can lead to reduced energy consumption of 10% [49]. Online shopping contributes to a large proportion of freight transport by road, as delivery vans around the country are vital for the last mile distribution of shopped goods. Better quality checks for defective items and responsible online shopping has the potential to reduce the rate of return from online shopping by 50% [41].

2.2.2. *Rail*

The identified demand reductions for passenger rail transport follow a similar pattern as private car reductions. A shift from public transport to bicycles could reduce the energy demand of rail transport by roughly 3% [14]. 21% of public transport is due to commuting and 11% of public transport is due to business travels [47]. Analogous to passenger car transport, these shares of public transport demand are assumed to be reduced by 20% through home office and 60% through telemeetings, respectively.

Rail freight transport has seen low levels of absolute growth in the EU compared to the road freight transport since 2000 [50]. The German government has identified the potential of trains in moving freight to reduce CO_2 emissions, as it emits the lowest amount of greenhouse gas emissions per ton-km [51]. Train speed control during operation has one of the highest potentials for reducing energy use. Controlling parameters, such as acceleration, cruising, and coasting, through optimization algorithms is capable of decreasing the present energy consumption by rail between 20–30% [52]. Using network optimization algorithms can also contribute to reducing energy consumption in rail freight transport. This would require support systems from the government, such as increased public investment in rail infrastructure and expansion planning based on time table intervals coordination [51]. Such optimization algorithms have the potential to reduce energy demand in rail freight scheduling by up to 14% [52].

2.2.3. *Aviation*

Aviation constitutes the greatest share of the mobility energy demand, suggesting that behavioral changes will show the most significant impact. In 2020, business flights decreased by 87% and private flights by 74%, which was certainly due to Covid-19 [53,54]. The pandemic has indicated that a lot of business meetings can actually be replaced by telemeetings. Up to 60% of passenger flights in Germany will be related to business travel in 2030 [24]. Assuming that the share of passenger flights related to business travels will gradually be replaced by telemeetings to the level that is possible already today, a significant saving potential is identified. Furthermore, assuming that flight behavior in Germany will change towards more sustainable behavior, the private flight rate of 2020 was taken as a basis for the reduction potentials. A total decline of 54% in passenger air demand is calculated.

Increasing freight traffic decreases the likelihood of significant energy reductions in freight aviation demand. A ton of freight transported by train instead of plane currently consumes more than 90% less energy and the energy consumption per ton of freight for ships is even lower.[3] In 2019, 22% of all cargo flights to and from Germany were continental flights (EU-27) [55]. Assuming that these flights could be replaced by ships and trains constitutes a saving potential of 20% in air freight transport in *Low Ambition* and approximately 30% in *High Ambition*, assuming that 10% of intercontinental flights could also be replaced.

The aggregated *Low Ambition* and *High Ambition* potential for the mobility sector is summarized in Table 3. It is derived by linking the discussed reductions with the respective shares of energy demand. Again, a negative percentage refers to the reductions that are derived for the respective category and percentages in the column headings refer to the share of total mobility demand, e.g. rail mobility energy demand accounts for approximately 10 percent of total mobility energy demand.

2.3. *Electricity sector*

The sector includes electricity used for traditional applications such as lighting, brown goods like information technology, white goods like refrigeration, and mechanical energy. So far, efficiency has played an important role in reducing conventional electricity consumption.

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[3] Own calculations. For a detailed description of the calculation process, see Zamora Blaumann et al. [41].

Table 4
Low and High Ambition reduction potential for residential, commercial and industrial conventional electricity demand.

Reduction potential	Residential (25.3%)	Commercial (28.9%)	Industrial (45.8%)	Total conventional electricity
Low Ambition	-4.0%	-5.5%	-7.0%	-5.8%
High Ambition	-20.0%	-23.4%	-17.5%	-19.9%

However, growing proliferation of appliances, increase in sizes and functionalities, longer usage hours, and new areas of application can be observed [28]. This can be partially attributed to rebound effects because when appliances become more efficient and therefore less energy-consuming, households can spend the saved income on other energy-intensive goods or increase the usage time of existing commodities [28,56]. This perspective indicates that efficiency alone will not be enough to achieve climate protection goals and societal behavior will play a decisive role the transformation of the energy system [44].

The total conventional electricity consumption is distributed between households (25.3%), commercial spaces (28.9%) and industry (45.8%) [42]. The highest share of electricity in households is used for low process heat (i.e. cooking and baking) and cooling. Also, information technology has a considerable share in electricity consumption. In the commercial sector, most electricity is used for lighting and other appliances, such as computers. In industry, the use of electricity to operate electric-driven motors and machines dominates the demand. The partition of households, commercial, and industry is used to identify measures in the literature and quantify their respective potential for demand reductions.

The literature focusing on behavioral changes in the electricity sector is scarce. While most of the studies assess the impact of efficient technology on demand, few evaluate the total potential of behavioral changes regarding conventional electricity. As stated in Fischer et al. [24], the main problem that arises in the evaluation of electricity reduction potentials is the partial overlapping of some implemented measures, making it difficult to sum them accurately. Table A1 in the Appendix presents an overview of the instruments and measures applied and their resulting reduction potential that were identified in the literature. Behavioral changes are differentiated by the instruments to incite the different behavior. For households, feedback systems seem to have a considerable effect in motivating households to reduce their electricity consumption. Martiskainen [57] use direct feedback, either from a smart meter or a display monitor, to assess the impact of knowledge on the amount of electricity consumed. They state that up to 15% of electricity can be saved together with setting a reduction goal. A more recent study by Zangheri et al. [58] estimates an average reduction potential by examining 64 studies mainly in Europe and North-America on different feedback applications, e.g. through in-home displays, load monitors, smart hubs, or energy portals, and state either a 9% reduction potential through direct or 4% through indirect feedback. BÃrger [59] has conducted one of the few country-level studies that evaluates the maximum achievable decrease in electricity use by ”lining up” various behavioral changes, such as optimizing the usage of different devices and avoiding stand-by losses. According to BÃrger [59], 20% of electricity could be saved in Germany. A similar approach is used in a study by Fischer et al. [24], which summarizes the energy demand reduction potential by 2030 in several sectors in Germany, including household appliances.

Energy consumption from non-residential buildings, like commercial offices, is more difficult to assess compared to typical households due to different building sizes, varieties of activities and since employees mostly share common equipment, making them feel less responsible for conserving energy [61]. For commercial spaces, Carrico and Riemer [61] and Nilsson et al. [62] both use group feedback systems and peer education as tools to change employee behavior and find 7% and 6% reduction in electricity consumption. Results in Hansen et al. [64] show an overall energy demand reduction of 10.5% due to changes in work and production schedule. As for industrial demand, Banks et al. [66] and Larsen et al. [65] have cited energy audits, energy and environment management systems, and voluntary agreements as possible measures to reduce energy in energy intensive sectors, as it pushes the entire organization to follow an internationally recognized process that influences overall energy consumption. Furthermore, Owen et al. [63] declare a 12% reduction potential through Community-Based Social Marketing, such as energy information and feedback systems. The findings of Hansen et al. [64] are partly transferred to industry, since office spaces are mostly utilizing the same lighting and equipment.

The overall potential for the *Low Ambition* and *High Ambition* scenario used hereafter is summarized in Table 4. It is derived by linking the reductions from literature with the respective shares of energy demand.[4] Again, a negative percentage refers to the reductions that are derived for the respective category and percentages in the column headings refer to the share of total conventional electricity demand, e.g. residential electricity demand accounts for approximately 25 percent of total conventional electricity demand.

3. Methodology and scenarios

The derived demand reduction potential based on behavioral changes is used as an input for an energy system model to investigate their impact on the supply side. Next, the methodical approach and the underlying data structure is briefly explained, followed by a detailed description of the modeled scenarios.

3.1. Applied model

For the evaluation of behavior-based demand reductions, a linear bottom-up planning model is employed. The model optimizes the German energy system in a greenfield approach and is implemented in the open-source, Julia-based framework *AnyMOD.jl*. The framework is developed to model complex energy systems with high spatial and temporal resolution. Main advantages of the framework include the flexibility to model energy carriers at different temporal resolutions [21,22].

Exogenous input to the model are cost assumptions, available technologies, conversion efficiencies, renewable potential and hourly time series for renewable availability and demand. To satisfy an exogenous final demand, the model decides on expansion and operation of technologies to generate, store, and transport energy carriers, while minimizing the sum of investment and operational costs. Since our focus is on a fully renewable energy system, the technology portfolio is limited to renewable technologies. The model has perfect foresight, meaning that hourly energy demand is fully known for the investment decision, and invests in renewable capacity to meet hourly demand for a single snapshot year 2050.

Fig. 2 provides an overview of the considered energy carriers and technologies and how they are interlinked. In the figure, carriers are symbolized by colored squares and technologies by gray circles. Edges between technologies and carriers indicate their relation and entering edges of technologies refer to input carriers; outgoing edges refer to outputs. For example, a gas plant takes synthetic gas as an input to generate electricity. The modeled technologies include generation and storage technologies. Generation technologies supply a certain carrier, often by converting energy from one form to another (e.g. from kinetic to electrical or electrical to chemical energy). Available generation technologies are photovoltaic (openspace, rooftop and agricultural[5]), wind turbines (onshore and offshore), hydrogen and synthetic gas turbines, electrolyzers and plants for methanation. Available storage

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[4] A more detailed description can be found in Zamora Blaumann et al. [41].

[5] Agricultural photovoltaic refers to solar panels that share space with conventional agricultural activity. The possible coexistence proves a high energetic potential on vast areas and dual-use opportunities.

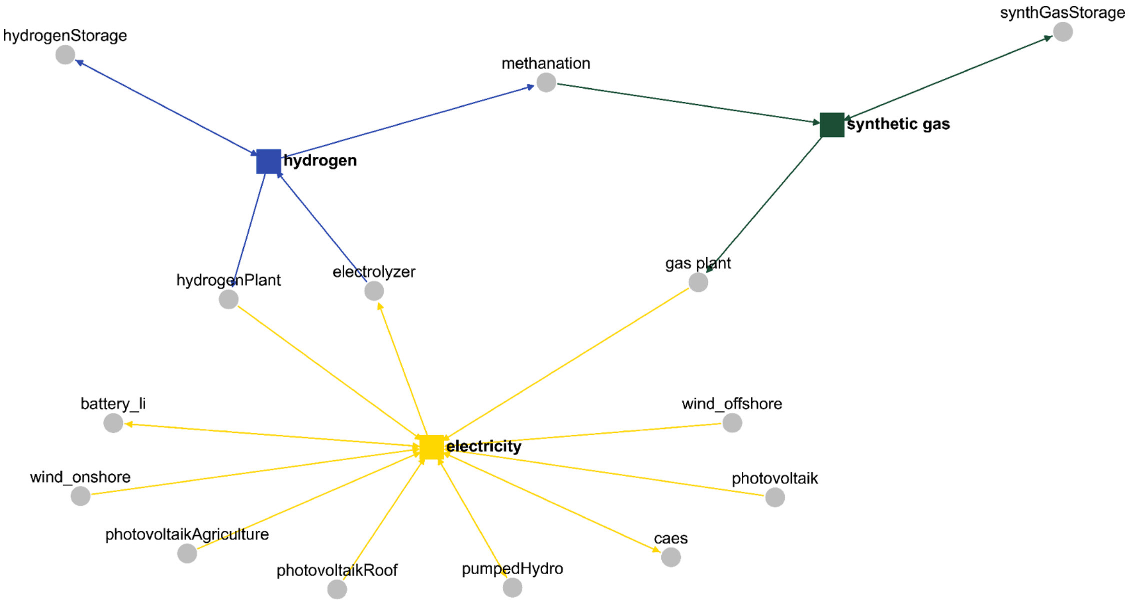

Fig. 2. Overview of modeled energy carriers and technologies.

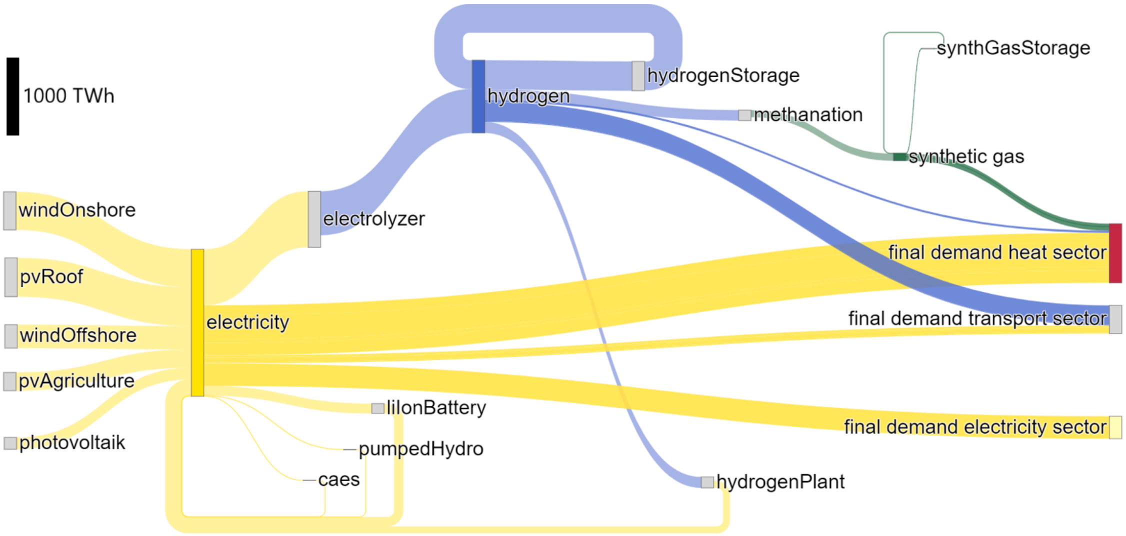

Fig. 3. Energy flow diagram of the reference case.

technologies are lithium-ion batteries, pumped hydro storages, gas storages and compressed air storages. Table B1 and B2 in the Appendix provide a comprehensive overview on the cost assumptions and data sources for generation and storage technologies. Fig. B1 in the Appendix shows the potential that limits the maximum capacity that can be installed for a specific technology [23,67].

To account for temporal variations in energy demand and renewable generation, both are implemented as hourly time series data from the *openENTRANCE* project [23].[6] The reductions identified in the previous section where deducted from the hourly time series in an equal proportion for every hour of the year. Fig. 3 shows a Sankey diagram visualizing the energy flow when solving the model in the reference case, meaning without any demand reductions. Final energy demand found on the right hand side of the diagram is separately provided for the heat, mobility, and electricity sector. The remainder of the diagram demonstrates how demand of these sectors is satisfied in the model by different technologies generating and storing energy.

Note that the stylized model does not consider import and exports of energy, which was adopted from other research and is a common approach when analyzing fundamental trade-offs in energy systems [70]. In addition, we assumed an unconstrained transport of energy within Germany. While these limitations reduce the applicability to real-world energy system, they focus the research on macro-level interactions between demand reductions based on behavioral changes and the rest of the energy system. This will be further discussed in Section 5.

3.2. Scenarios

To distinguish between different levels of behavioral change, the demand reductions are implemented in two scenarios. Fig. 4 presents the demand reductions assumed for the *Low Ambition* and *High Ambition* scenario with dark colors representing the energy demand that still needs to be met, and lighter colors representing demand reductions based on behavioral changes for each sector. The exact corresponding values are listed in Table 5. Percentages refer to the reduction relative to

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[6] For details see Fig. B2 the Appendix.

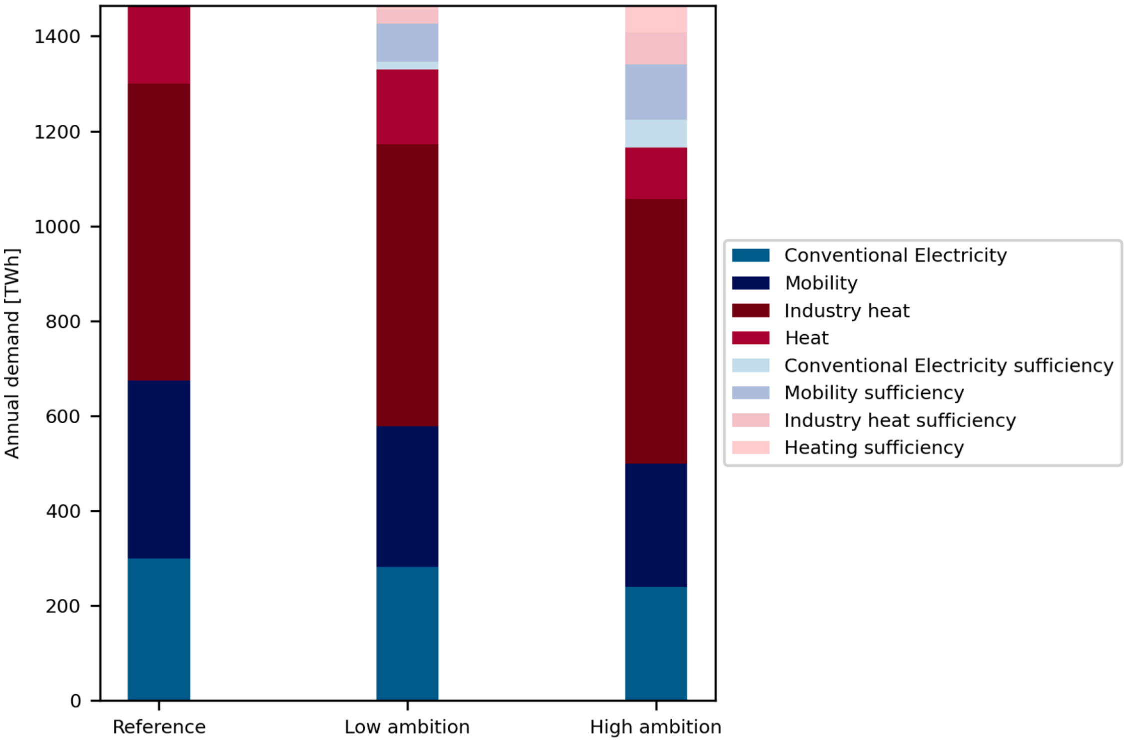


Fig. 4. Visualization of the composition of the energy demand across scenarios.

Table 5
Behavior-based demand reductions in each sector.

Scenario	Conventional Electricity	Mobility	Residential/ Commercial Heat	Process Heat	Total
Low Ambition	-5.8%	-21.7%	-5.0%	-4.9%	-9.4%
High Ambition	-19.9%	-30.9%	-34.2%	-10.9%	-20.5%

Table 6
Total annualized system costs and demand reductions in the reference, *Low Ambition* and *High Ambition* scenario.

	Reference	Low	High
Total costs [Mil. €]	119,399	105,897	88,867
Cost	0%	-11.3%	-25.6%
Total demand	0%	-9.4%	-20.5%

Table 7
Overview on total system cost and demand reductions by sector.

Sector	Total System Costs [Mil. €]	Cost reduction	Demand reduction
Reference	119,399	0.0%	0.0%
Electricity	113,888	4.6%	4.1%
Transport	108,656	9.0%	8.0%
Heat (a+b)	104,731	12.3%	8.3%
a. Heat residential	111,889	6.3%	3.9%
b. Process heat	112,229	6.0%	4.5%

the individual sector demand, e.g. mobility reduction potential refers to 30.9% of the mobility energy demand. There are no specific assumptions on the temporal structure of demand reductions and relative reductions are applied equally to each hour of the year, which translates to a proportional downward shift of the load curve.

3.3. Sensitivity analysis

An additional sensitivity analysis investigates the impact of each sector individually. In this case, only the assumptions of the *High Ambition* scenario are applied for each sector individually to allow for a comparison of sector-specific effects on the supply side. As a result, the quantitative difference of sectoral reductions can be elaborated on.

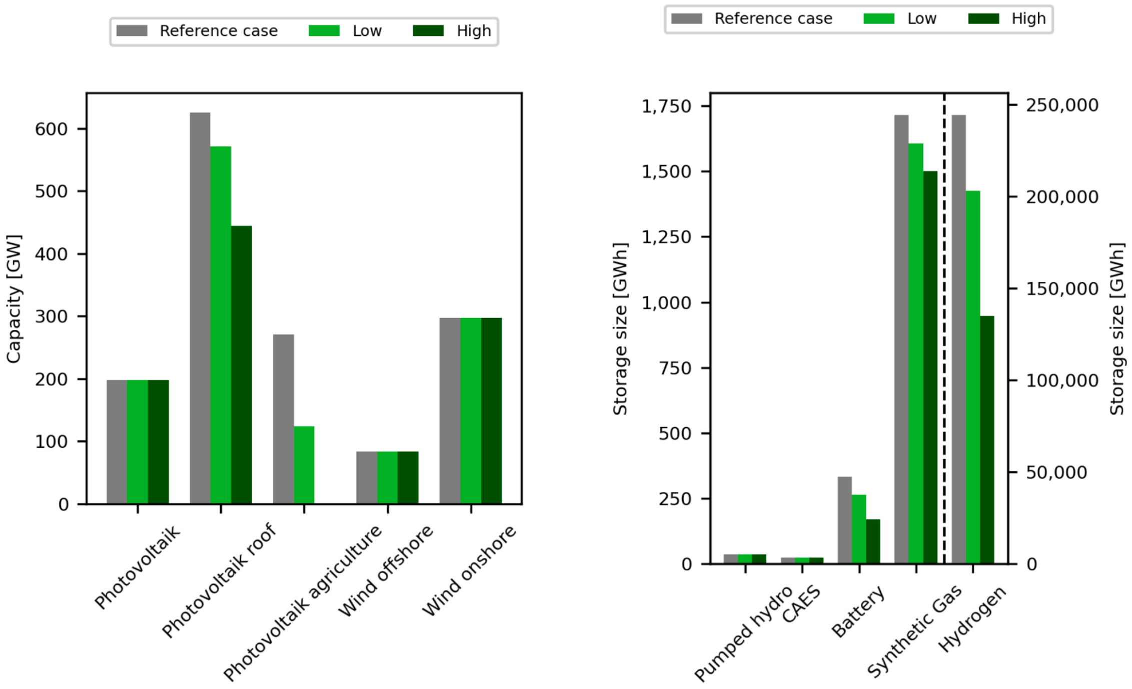
4. Results

The results of the energy system model for the different scenarios can be used to estimate the impact of behavioral changes. Key results include cost savings and the impact on generation and storage capacities.

4.1. Scenario results

Demand reductions from the *Low Ambition* and *High Ambition* scenario result in a reduction of system costs by 11.3% and 25.6% respectively, as listed in Table 6. There is an overproportional decrease in costs from *Low Ambition* to *High Ambition*, because demand decreases by 11.1% in between the scenarios, but cost by 14.3%. This is due to the higher reduction of the demand for synthetic gas in the *High Ambition* scenario, resulting in larger cost savings given the conversion losses from electrolysis and methanation versus direct use of electricity.

The demand reductions in the *Low Ambition* and *High Ambition* scenario lead to an overall renewable capacity reduction of 13.6% and 30.6% respectively, as well as a storage size reduction of 16.8% and 44.5%. Fig. 5 details the capacity reductions in each technology, reporting that the need for capacity and storage is decreasing relative to



(a) Capacity of renewable technologies

(b) Size of storage technologies

Fig. 5. Model results of scenarios. Installed renewable generation capacities (a) and storage size (b) for *Low Ambition* and *High Ambition*.

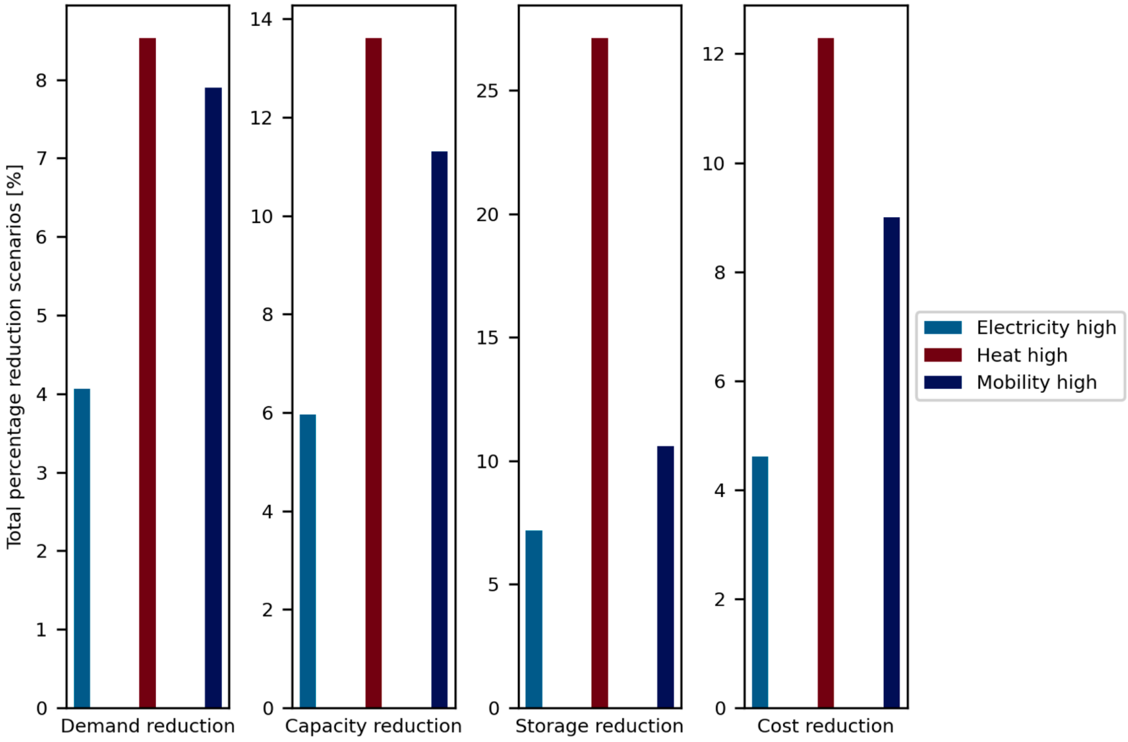


Fig. 6. Impact of assumptions in the high ambitions scenario on each sector.

demand. The most significant storage reduction comes from hydrogen storage, as shown in Fig. 5b, because the need for long term storage decreases. Necessary generation capacity is reduced for agricultural and rooftop photovoltaic, probably explained by high capacity costs due to the limited availability of solar radiation. In the *High Ambition* scenario, the overall photovoltaic capacity is reduced by 41.3%, and agricultural photovoltaic is not necessary at all.

4.2. *Sensitivity analysis*

Fig. 6 compares effects of the individual sectors on generation capacities, storage sizes and total annualized system costs. In each case, only one sector's demand is reduced, while the other two remain unchanged. The heat and transport sector have a demand reduction potential of about 8% of the total energy demand, visible in the left subplot of Fig. 6. It is noticeable that reductions of the same magnitude lead to storage reduction of approximately 11% for the transport sector and 27% for the heat sector. Therefore, substantial cost savings for storage technologies can be archieved, in particular by reducing the required capacities of li-ion batteries, saving 1,500 million euro of annualized costs.

Because of high peak loads, behavioral changes in the heating sector show the highest impact on the systems supply side, as demand reductions lead to over-proportional cost reductions. The peak loads for each sector are depicted in the load duration curve in Fig. B2. For example, residential heat indicates cost savings 1.6 times larger than the applied demand reduction and process heat shows cost savings 1.4 times larger than the applied demand reduction. In comparison, behavioral changes in the transport and electricity sector lead to cost savings that are only 1.1 times larger than the demand reduction. In total, the heating sector reaches the highest cost reduction of 12.3% compared to the reference case.[7]

5. Discussion

This paper analyzed how behavior-based demand reductions can support the decarbonization of the energy system and result in cost and capacity savings. The assessment of the potential of behavioral changes is still subject to a number of limitations influencing the obtained results, both in terms of argumentation and method.

Firstly, this analysis does not consider the multiple impacts of demand reductions on other areas, such as social impacts, health or gross domestic product. For example, behavioral changes that are associated with a decreased consumption of products would also impact job creation in the affected business area. Furthermore, we do not attach any costs to the behavior-based demand reductions, but promoting and achieving some of the changes includes substantial infrastructure investments, for example investments in cycling and public transport infrastructure. Neglecting impacts on other areas also restricts the performed quantitative cost analysis. Analysis is limited to the techno-economic energy system and its costs inevitably decrease when final demand is reduced, but these reductions are not weighted against the costs and benefits in other areas.

Moreover, the demand reductions identified in the paper were implemented without assessing the political feasibility. For example, Covid-19 has shown that realizing high shares of home office and telemeetings are indeed possible, but occurred in a heavy lockdown with strong state interference. This indicates that the demand reduction potentials actually exist, but how this potential can be utilized remains an issue for future research and would require significant changes in the political framework and in society. The realization of some potentials seems to be difficult, for example promoting a decreased living space per person or a lower room temperature. However, while all of this need to be considered when interpreting the results of this paper, we argue that if the suggested behavioral changes are accompanied by a broader transformation of the economy, they would most likely increase the collective quality of living by finding a level of “enoughness” that allows for a decent living standard for all while still respecting planetary boundaries. For example, low-energy behavior might occur intrinsically when knowing that it is part of a greater transformation to mitigate climate change that avoids greater damage in future. Günther et al. [15] conclude that a societal rethink is necessary, which requires the political creation of the necessary regulatory, social and economic framework conditions as well as educational policy measures.

Secondly, some limitations apply to the quantification of the potentials and how they are implemented into the bottom-up planning model, especially regarding modal shifts towards public transport. Modal shifts are certainly a key leverage for reducing absolute energy demand in the transport sector, but are complex to quantify since they are rather an energy substitution than a reduction, a fundamental difference to other included behavioral changes. For instance, a 5% reduction in residential heat demand due to lower temperatures can directly be translated into a corresponding reduction of energy demand. In contrast, a model shift, for instance from road to rail transport, will decrease energy demand for road transport, but increase demand for rail transport, typically resulting in a net reduction. Quantifying the increase of energy demand in public transport due to a model shift requires additional assumptions: Means of public transportation range from shared taxis to metrolines and greatly differ in energy demand. Accordingly, the modal shift must be broken down to these means and specific energy demands per transported passenger must be assumed. This energy demand will again greatly depend on supply and utilization of transport services. For instance, if a modal shift is achieved without extending public services, but only increase its utilization, energy demand will not change substantially. If transport services are extended and as result also average utilization decreases, energy demand will increase disproportionately. In conclusion, we excluded the analysis of modal shifts involving public transport, not because there is a lack of estimates or historical data on the shift itself, but because translation into energy demands is an obstacle. This step requires in-depth modelling of the transport sector, which exceeds the scope of our paper, but was part of previous more comprehensive scenario studies [15,16,18].

In addition, dependencies of demand reductions in between sectors have not been considered in this analysis. For example, a reduction of aviation would also decrease the energy demand in the manufacturing industry for air planes. More research on the temporal occurrence of behavior-based demand reductions would help to understand whether certain behavioral changes have a higher impact on system cost and required capacities. The findings of this paper suggest that reductions in the heat sector have the highest impact on system cost due to the high peak loads of this sector. Applying the demand reductions time-specific could further refine these findings and help to identify key leverages with large benefits for the energy system.

Finally, the applied energy system model is stylized. For example, it still neglects cross-border exchange of energy and does not consider transition pathways. Power flows and transmission bottlenecks in the grid are not considered due to the copperplate approach. These factors are in particular relevant when analyzing an energy system with 100% renewable energies and the state-of-the-art in bottom-up planning models for highly renewable energy systems is usually more detailed. As the focus of this analysis is on behavioral changes, it should therefore not be interpreted as a technical analysis of the feasibility of a 100% renewable energy system.

Our research identified a behavior-based demand reduction potential of 300 TWh in *High Ambition*, which translates to 1165 TWh final energy demand when subtracted from a reference demand of 1465 TWh. The results of the bottom-up planning model showed a significant impact of the demands reductions on required renewable capacities and system costs. This confirms previous findings from the few quantitative studies that explicitly incorporated behavioral changes. The demand reductions identified through behavioral changes in Sterchele et al. [16] are with 320 TWh in the same range, but start from a reference energy demand of 1902 TWh in 2045. The behavior-based demand reduction potential in Günther et al. [15] is not explicitly stated, but the scenarios including behavioral changes have a final energy demand of approximately 1450 TWh (*Green Life*) and 1300 TWh (*Green Supreme*). In comparison, other studies that analyze a decarbonized German energy system estimate a final energy demand between 1598 TWh to 1116 TWh [17–20,71]. This indicates that there is still a high level of uncertainty on the absolute magnitude of final energy demand, which complicates quantifying the benefits of behavior-based demand reductions.

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[7] “Heat residential” includes the private and commercial heat demand at this point.

6. Conclusion

The decarbonization necessitates a rapid transformation of energy systems, which includes a massive expansion of renewable generation capacity. Quantitative energy system models that include all sectors are increasingly employed to understand the complex relationships of a 100% renewable energy system. While many quantitative studies model a decarbonized energy system, few include absolute reductions in final energy demand based on behavioral changes in their scenarios. This research has therefore explicitly investigated the potential of behavioral changes to reduce final energy demand and estimated the impacts on the supply side of a 100% renewable energy system in Germany.

Based on literature, the behavior-based demand reduction potential was quantified for two different levels of ambition, serving as the scenarios *Low Ambition* and *High Ambition*. An overall demand reduction potential of 9.4% to 20.5% has been identified, respectively. Reference energy demand of 1465 TWh is thus reduced by 138 TWh to 1327 TWh in *Low Ambition* and by 300 TWh to 1165 TWh in *High Ambition*. The heat and transport sector show demand reduction potentials of 124 to 115 TWh respectively, followed by the electricity sector with up to 60 TWh reduction potential.

The impact these reductions have on the supply side of the energy system was evaluated using a cost-minimizing bottom-up planning model for the scenarios *Low Ambition* and *High Ambition*. Results when considering behavioral changes were compared against a reference case without any behavioral changes. The results show that behavioral changes can achieve cost savings of up to 25.6% and reduce generation and storage capacity by 30.6% and 44.5% in *High Ambition*. The potential cost savings from behavioral changes are the most significant in the heat sector due to its high peak loads. Final energy demand in the heat sector can be reduced by 8.3%, resulting in over-proportional cost savings of 12.3%. In comparison, demand reduction of 4.1% in the electricity and 8% in the transport sector show only a cost reduction of 4.6% and 9%, respectively.

As pointed out in previous literature [15,16], our quantitative evaluation suggests significant benefits from considering behavioral changes for decarbonization. On the one hand, this means future research should dedicate further efforts to quantify the sector-specific potential for demand reductions based on behavioral changes. Results in this study were based on a literature review and should be considered first estimates that can be further refined by sector-specific analysis. For example, it appears promising to combine detailed models of residential heat demand with a comprehensive energy system model for a highly resolved analysis of behavioral changes in this area.

On the other hand, scenarios for public policy should take greater account of potential behavioral changes and future research should evaluate adequate policy instruments to promote absolute reductions in final energy demand. In policy, a framework to promote and increase the likelihood of low-energy behavior is still missing. For example, policies that target low-energy behavior could aim at the size of end-use equipment, discourage individual property in favor of a shared economy and promote shared living space or reduce aviation frequency and length [4]. Behavior-based demand reductions could be included in at least one scenario in every scenario-based analysis to depict possible decarbonization pathways' bandwidth accurately in scientific research. In conclusion, the most eco-friendly kilowatt hour is the one that is not consumed.

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.

Acknowledgments

We thank Carl-Christian Kloetzsch, Eric Rockstaedt, Michel Kevin Caibigan, Morteza Lavaiyan and Nithish Kini Ullal for their collaboration in this project.

Appendix A

Sufficiency-based demand reductions

Table A1
Behaviour-based demand reductions from literature in the sector conventional electricity. Measures refer to the causes that induce demand reductions, the value range refers to the reductions range that was identified in literature. Measures can either be politically promoted or occur due to changes in socio-economic norms.

Sub-category	Measures	Value range	Source
Residential			
	Direct feedback	-5.0% to -15.0%	Martiskainen [57]
	Direct feedback applications (Europe and N.America)	-9.0%	Zangheri et al. [58]
	Indirect feedback applications (Europe and N.America)	-4.0%	Zangheri et al. [58]
	Goal setting	-4.5%	Martiskainen [57]
	Goal setting with feedback	-15.1%	Martiskainen [57]
	Feedback through smart meters and time-use tariffs (Ireland)	-1.8%	Carroll et al. [60]
	Feedback (peak reduction)	-7.8%	Carroll et al. [60]
Behavioral change through intervention	Change of human behavior	-20.0%	BÃrger [59]
	Sufficiency in lighting and appliances	-15.0% to -20.0%	Fischer et al. [24]
Change in user behavior through intrinsic motivation	Change of human behavior	-20.0%	BÃrger [59]
Commercial			
	Group level feedback	-7.0%	Carrico and Riemer [61]
	Goal setting	-12.9%	Nilsson et al. [62]
Behavioral change through intervention	Goal setting with feedback etc.	-5.5% and -6.0%	Nilsson et al. [62]
Behavioral change through use of technology	Energy information system + social marketing - feedback (Community Based Social Marketing)	-12.0%	Owen et al. [63]
Revolutionary changes through legislations	Four-day week/shorter working time/less production	-10.5%	Hansen et al. [64]
Industrial			
	Energy Audits (Denmark)	-7.0% to -20.0%	Larsen et al. [65]
Behavioral change through intervention	Energy information system + social marketing - feedback (Community Based Social Marketing)	-12.0%	Owen et al. [63]
Revolutionary changes through legislations	Four-day week/ shorter working time/ less production	-10.5%	Hansen et al. [64]

Table A2
Behaviour-based demand reductions from literature in the sector mobility. Measures refer to the causes that induce demand reductions, the value range refers to the reductions range that was identified in literature. Measures can either be politically promoted or occur due to changes in socio-economic norms.

Measure	Value range	Source
Bicycles		
Modal shift from passenger car to cycling	-3.5% to -10.0%	Fischer et al. [24], Van de Ven et al. [43]
Increased level of investment in bike infrastructure	+50.0% to +100.0%	Venturini et al. [46]
Increased share of E-Bikes in total	+1.0% to +50.0%	Venturini et al. [46]
Passenger cars		
Replacing business trips with telemeetings	-40.0% to -60.0%	Fischer et al. [24]
Smaller passenger cars through regulation	-7.5%	Fischer et al. [24]
Reduction of motorized individual transportation	-30.0%	Sterchele et al. [44]
Reduced commuting demand through teleworking	-1.0% to -20.0%	Van de Ven et al. [43], Venturini et al. [46]
Increased load factor for every commute car trip (carpooling)	Load factor 2	Van de Ven et al. [43], Venturini et al. [46]
Public transport		
Modal shift to public transport for all commuting demand	-100.0%	Van de Ven et al. [43]
Reduced traveling time of public transport	-1.0% to -10.0%	Venturini et al. [46]
Aviation		
Reduction of aviation	-55.0%	Sterchele et al. [44]
Reduction of private aviation	-50.0%	Fischer et al. [24]
Avoid flights that can be replaced by another transport mode <10h	-25.0%	Van de Ven et al. [43]
Replace intercontinental leisure flights with intra-EU trips	-50.0%	Van de Ven et al. [43]

Appendix B

Model input data

Table A3
Behaviour-based demand reductions from literature in the sector heat. Measures refer to the causes that induce demand reductions, the value range refers to the reductions range that was identified in literature. Measures can either be politically promoted or occur due to changes in socio-economic norms.

Measure *Space heating demand*	Value range	Source
Lowering average room temperature by 1–2° C	-4.4% to -9.0%	Fischer et al. [24], Marshall et al. [25]
Turning down thermostat by 1° C	-13.0%	Palmer et al. [26]
Decreasing living space per person	-24.9% to 35.7%	Bierwirth and Thomas [27]
Hot water consumption		
Water efficient shower heads	-50.0%	Palmer et al. [26]
Feedback system about showering time	-5.0% to -10.0%	Toulouse and Attali [28]
Shorter and less frequent showering	-20.0% to -30.0%	Palmer et al. [26]
Adjusting water consumption	-70.0%	Lehmann et al. [29]
Process heat low temperature		
Decreasing food waste	-8.6% to -13.2%	Schmidt et al. [30] Vita et al. [31]
Process heat mid temperature		
Increasing plastic recycling	-1.4% to -2.1%	Association ngaWatt [32], Umweltbundesamt [33] Verband der Chemischen Industrie [34]
Extending useful life of products and establishing service-based sharing economy	-3.0% to -8.2%	Vita et al. [31], Prakash et al. [35]
Modal shift construction products and reduced construction materials	-0.7% to -1.7%	Hertwich et al. [36]
Process heat high temperature		
Modal shift construction products and reduced construction materials	-3.0% to -7.6%	Hertwich et al. [36]

Table B1
2035 Technology cost assumptions.

Technology	**Investment Costs [€/kW]**	**Operating Costs [€/kW]**	**Lifetime [Years]**	**Source**
ccgtGas	345	8.6	30	Auer et al. [23]
ccgtHydrogen	185	3.3	30	Auer et al. [23]
Methantion	865	18	30	GÃüe et al. [68]
Electrolyzer	543	14.6	30	GÃüe et al. [68]
PV	407	7.9	25	Auer et al. [23]
PV Rooftop	594	11.5	25	Auer et al. [23]
PV Agriculture	814	7.9	25	Kost et al. [69] Trommsdorff [67]
Wind Onshore	1200	30	25	Auer et al. [23]
Wind Offshore	3111	100	25	Auer et al. [23]

Table B2
2035 Storage cost assumptions.

Technology	Investment Costs [€/kWh]	Investment Costs [€/kWh]	Lifetime [Years]	Source
Li-Ion Battery	218	84.2	18	GÃüe et al. [68]
Pumped Hydro	10	745	60	GÃüe et al. [68]
Gas Storage	0.1	0.1	30	GÃüe et al. [68]
CAES	26.4	455	30	GÃüe et al. [68]

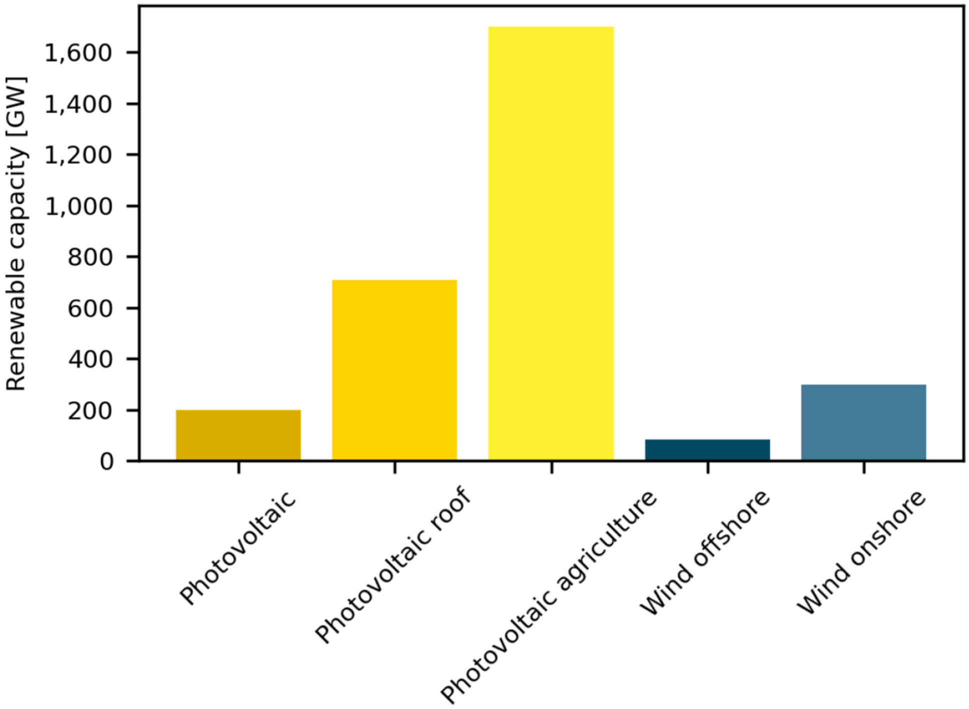

Fig. B1. Renewable potentials in gigawatt [GW] by technology. Potentials are mainly restricted by land availability. The model can invest into each technology until the limits are met. Own illustration based on Auer et al. [23].

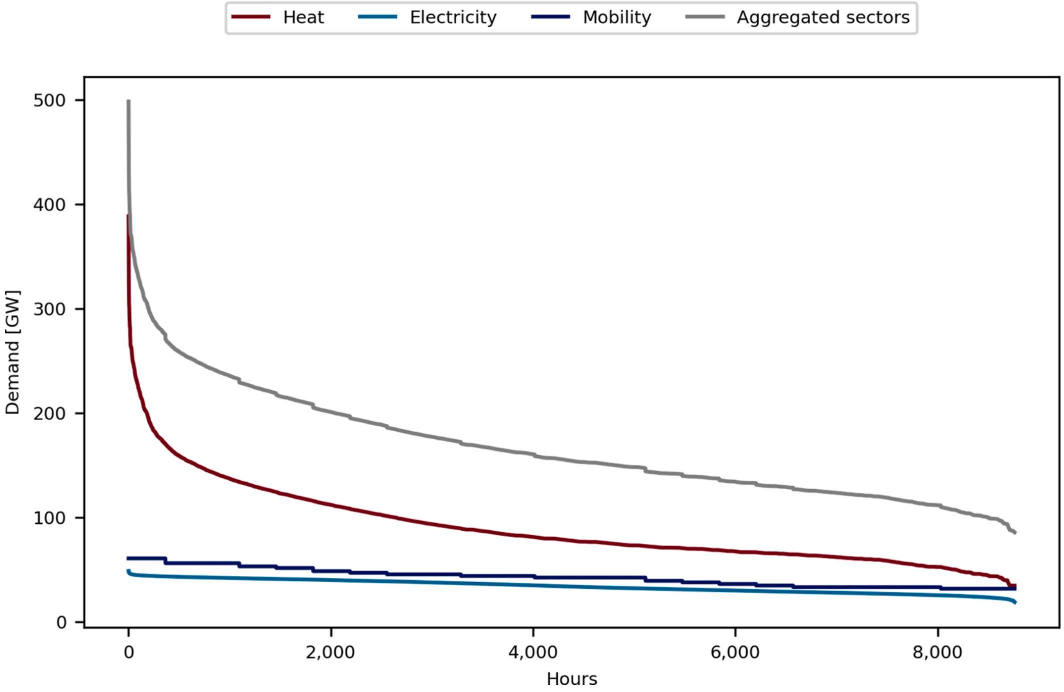

Fig. B2. Sectoral and aggregated load curve in reference case. Hourly load in GW is depicted in descending order. Own illustration based on Auer et al. [23].

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