Technical University of Berlin
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Energy Economics - Student Research Project

The Potential of Sufficiency Measures to Achieve a Fully Renewable Energy System

A case study for Germany

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Abstract

Although behavioural changes during the COVID-19 pandemic lead to a noteable drop in annual emissions, these effects are expected to be negligible, because no sustainable change in behaviour can be observed. The growing body of scientific literature on the required low-carbon transformation of the energy system is mostly focusing technological supply side solutions. On the other hand, the demand side receives far less attention, despite having high potential for mitigation. In contrast to research on energy efficiency, the concept of energy sufficiency remains rather unexplored, although lifestyle changes towards a low-energy-demand future are also increasingly associated with greater human well-being and satisfaction.

This paper therefore strives to answer the following question: What is the potential of sufficiency-based demand reductions and what impacts do they have on the supply side of a 100% renewable energy system? Based on a literature review, alternative demand pathways for the sectors heat, mobility and conventional electricity are derived. A demand reduction potential through behavioural changes of up to 20.5% is identified, resulting in total annual demand reductions of 300 TWh.

A least-cost capacity expansion model is applied to estimate the impacts of these reductions on a greenfield, renewable energy supply for Germany in a scenario-based approach. Overall results indicate that cost reductions of 11.3% to 25.6% in comparison to no lifestyle changes are possible. The sectoral analysis shows that due to high peak loads, demand reductions in the heat sector are significantly more cost-effective than demand reductions in the mobility and conventional electricity sector. A further sensitivity analysis confirms that by cutting demand peaks, less than 1% of overall demand reduction decreases the cost-optimal generation capacity by 2% and storage capacity by 5%. Overall, this paper finds that (a) human lifestyle changes have great potential to reduce energy consumption, (b) the impacts on the supply side are significant and (c) should therefore be included in energy modeling and policy advice.

Executive Summary

Although there was a slight drop in annual emissions due to COVID-19, global emissions continue to increase and the pandemic is expected to have negligible long-term effect on climate change. Whereas a growing number of countries are committing to net-zero emissions by 2050, the Nationally Determined Contributions (NDC) reveal a massive remaining emission gap of current policies with at least 3 ℃ of global warming by the end of the century (UNEP, 2020). Hence, the climate crisis delivers an undeniable motivation for a rapid transformation of the energy system.

There is a growing variety of approaches to enable a zero-carbon transformation. A majority of scientific papers that aim at advising public policy focus mainly on technological supply-side solutions. The demand-side solutions tend to receive far less attention, although they have a high potential for mitigation and are associated with far less risk than the supply side technologies. A growing body of scientific literature indicates that demand side solutions are required to stay within 1.5 ℃ degrees. Whereas their focus mostly lies on energy efficiency, the concept of energy sufficiency remains rather unexplored. However, besides the contribution to the climate change mitigation, lifestyle changes towards a low-energy-demand future are increasingly associated with greater human well-being and satisfaction. This paper connects the demand-side solutions with the supply-side and strives to answer the following question: What is the potential of sufficiency-based demand reductions and what impacts do they have on the supply side of a 100% renewable energy system in Germany?

A cost-minimizing capacity expansion model is applied to estimate the impacts of these reductions on a greenfield, renewable energy supply for Germany in a scenario-based approach. The model is implemented in the AnyMOD Framework (Göke, 2020a; Göke, 2020b), graph-based framework that facilitates modeling high levels of renewable resources and sector integration. The model's objective consists of capacity expansion costs, energy system operating plus variable costs, and energy trade costs. There is a list of predefined parameters for the set of carriers and technologies in the model which are used to assign value to them in order to create the desired energy system. The model's constraints ensure that the hourly demand for each carrier in each sector is fulfilled. In this regard, the required capacity to expand, generate, store and transport the energy in all sort of available carriers and technologies are calculated and compromised separately.

The technology input files are split into two categories, conversion technologies and storage technologies. The conversion technologies convert energy from one form to another (an electrolyzer converts electrical energy to chemical energy), or generate energy (such as wind or

solar). The following conversion technologies are included in the model input parameters: rooftop photovoltaic (PV), open-space PV (ground-mounted), agricultural PV (raised ground-mounted above partial-shade crops), on-shore and off-shore wind, hydrogen plant, electrolyzer, and methanation. The costs assumed for capacity expansion for these technologies is taken from projections made by Kost et al. (2018) (photovoltaic and wind) and Göke et al. (2019) (electrolyzer and methanation). The capacity limits for onshore wind and solar are split into six regions of Germany (East, West, Northeast, Northwest, Southeast, and Southwest) on an hourly basis for an average year. The offshore wind capacity is treated as one region, and similarly is on an hourly basis for one year. The capacity assumptions are derived from openENTRANCE[1], a European Union Horizon 2020 funded project. The following storage technologies are included in the model: Li-ion batteries, Compressed Air Energy Storage (CAES), pumped hydroelectric storage (involving two reservoirs of different elevations, water is pumped/released during times of varying demand, storing/recapturing the energy), synthetic gas storage, and hydrogen storage. The price assumptions for these technologies are taken from Kost et al. (2018).

The model employed splits the energy system into three sectors: heat, mobility, and conventional electricity. Based on a literature review, alternative demand pathways for these sectors are derived. A demand reduction potential through behavioural changes of up to 20.5% is identified, resulting in a total demand reductions of approximately 300 TWh. After extensive literature review, reasonable demand reductions of 9.4% and 20.5% in Low and High ambition scenarios are assumed, respectively. These reductions result in cost reductions of 11.3% to 25.6% in comparison to current consumption patterns. These demand reductions are applied in an integrated scenario in two ways - by proportional demand reduction across all timesteps, and by reducing only the peak load hours. These percentage demand reductions of a combined Low ambition scenario equal a peak hour shedding at 163 GW, analogously the combined High ambition scenario and the peak hours cut at 134 GW equal in amount of demand reduction. Storage reduction for the combined Low scenario reach a level of 16%, while the same demand reduction in the peak load hours only, reach a storage saving of 45%. Furthermore, savings in renewable capacity are visible, even though they are respectively small compared to additional storage size savings. The renewable capacity savings for the combined Low scenario is 13% while that of the peak hour shedding at 134 GW is almost 3% more.

The sectoral analysis shows that due to high peak loads, demand reductions in the heat sector are significantly more cost-effective than demand reductions in the mobility and conventional

[1] Read more about openENTRANCE at https://openentrance.eu/

electricity sector. A further sensitivity analysis confirms cutting demand peaks can have an outsized impact on the capacity and storage required to meet demand, compared to proportional demand reduction. Overall, this paper finds that human lifestyle changes have the potential to significantly reduce energy consumption, and these reductions have meaningful impacts on the cost required to meet demand with a 100% renewable energy system. These ideas and concepts should therefore be included in energy modeling and policy advice, and are deserving of further inspection.

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Acronyms

CAES	Compressed Air Energy Storage
CBSM	Community-Based Social Marketing
CCTS	Carbon-Capture-Transport-and-Storage
eceee	European Council for an Energy Efficient Economy
GCAM	Global Change Assessment Model
GHG	Greenhouse Gas
ICT	information and communication technology
MIT	Motorized Individual Transport
NDC	Nationally Determined Contributions
PV	photovoltaic
RES	Renewable Energy Sources

1. Introduction

Although behavioural changes during the COVID-19 pandemic lead to a noteable drop in annual emissions, these effects are expected to be negligible, because no sustainable change in behaviour can be observed. 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℃ of global warming is rapidly shrinking (Friedlingstein et al., 2019; Peters et al., 2020; Mundaca et al., 2019). Although there is a growing number of countries committing to net-zero emissions by 2050, the Nationally Determined Contributions (NDC) reveal a massive remaining emissions gap of current policies, resulting in at least 3℃ of global warming projected by the end of the century (UNEP, 2020).

There is a large and growing variety of approaches to enable a zero-carbon transformation, but a majority of scientific papers that aim at advising public policy focus on technological supply side solutions. Emerging pathway literature widely includes Carbon-Capture-Transport-and-Storage (CCTS), nuclear energy and a large-scale deployment of hydrogen to decarbonize the supply side. In contrast, demand side solutions receive far less attention, although they have high potential for mitigation and are associated with far less risk than the mentioned supply side technologies. Approximately two thirds of global emissions are linked to private households in consumption-based accounting, and final energy use is the most inefficient part of the energy system (Grubler et al., 2018; Samadi et al., 2017; UNEP, 2020). Simultaneously, a growing body of scientific literature indicates that demand side solutions are required to stay within 1.5 ℃ degrees. The existing demand side solutions are not only insufficiently covered by quantitative energy system models, but also strongly focus on energy efficiency. In contrast, the concept of energy sufficiency remains rather unexplored, although lifestyle changes towards a low-energy-demand future are also increasingly associated with greater human well-being and satisfaction. This paper therefore strives to answer the following question: What is the potential of sufficiency-based demand reductions and what impacts do they have on the supply side of a 100% renewable energy system in Germany?

Based on a extensive literature review, alternative demand pathways for the sectors heat, mobility and conventional electricity are derived. A demand reduction potential through behavioral changes of up to 20.5% is identified, resulting in total demand reductions of 300 TWh. A least-cost capacity expansion model is applied to estimate the impacts of these reductions on a greenfield, renewable energy supply for Germany in a scenario-based approach. The model is implemented in the AnyMOD Framework (Göke, 2020a; Göke, 2020b) with renewable availability time series in a high temporal resolution and technology cost assumptions for 2035. Overall results indicate that cost reductions of 11.3% to 25.6% in comparison to no lifestyle changes are possible. The sectoral analysis shows that due to high peak loads, demand reductions in the heat sector are significantly more cost-effective than demand reductions in the mobility and conventional electricity sector. A further sensitivity analysis confirms that by cutting demand peaks, less than 1% of overall demand reduction decreases the cost-optimal generation capacity by 2% and storage capacity by 5%. Overall, this paper finds that (a) human lifestyle changes have the potential to reduce energy consumption, (b) the impacts on the supply side are significant and (c) should therefore be included in energy modeling and policy advice.

The following analysis is structured as follows: Section 2 provides an overview on the existing literature that relates to sufficiency in existing capacity expansion modeling studies and the economic aspect of behavioral changes. The potential for sufficiency-based demand reductions in the three sectors is quantified in Section 3. Section 4 contains a description of the applied model, including the relevant input data and cost assumptions. The demand reduction potential identified in Section 3 is translated to sector-specific scenarios in Section 5. The scenarios for the combined sectoral analysis are described in Section 6, including a sensitivity analysis on peak load shedding. Section 7 discusses the most relevant results and Section 8 concludes.

2. Literature Review

In this Section, first the theoretical background of sufficiency is briefly explained. Then, the related literature on incorporating behavioural change of demand for energy services in energy system modelling is concisely expressed. The related literature on quantifying potential sufficiency measures in the three sectors chosen for this study will be elaborated in Section 3.

2.1. Theoretical background

Similar to any other intellectual concept, there have been several definitions for the term "energy sufficiency" in the related literature. Here, some of the main and explicit ones are provided. According to Darby and Fawcett (2018), energy sufficiency is defined as "a state in which humanity would only consume energy services equitably and in quantities compatible with sustainability and ecological limits". Regarding energy sufficiency as a strategy, Toulouse, Le Dû, et al. (2017) describe it as "favoring behaviours and activities that are intrinsically low on energy use". In the Energy Sufficiency Project which is run by the European Council for an Energy Efficient Economy (eceee), energy sufficiency is described as "the situation where everyone has access to all the energy services they need and a fair share of the energy services they want whilst, at the same time, the impacts of the energy system do not exceed environmental limits"[2].

These definitions promote the differences between "energy" and "energy services" to better capture the idea behind what sufficiency means in this context. Energy services are assumed to be the utility which is gained by consuming energy in different manners and in various conditions (Toulouse, Sahakian, et al., 2019). With this focus on energy services instead of energy itself, it is easier to realize the notion of sufficiency in terms of meeting the needs and not consuming too much. Moreover, the definitions focus on people's needs to indicate the difference between needs and wants. Proposed by social and philosophical sciences where there have been efforts to define the universal human needs, the debate on how to distinguish the necessities and preferences remains in the relevant literature of energy services as well (Wilhite and Norgard, 2003). The theory of need put forward by Gough (Gough, 2015; Gough, 2017) brings forth the basis for sufficiency as it outlines the distinction between wants that are derived from preferences and needs that are vital for social and physical survival of humanity. It is worth to mention that he refers to social needs, being elucidated as essential capabilities of chasing one's goals and dreams in life (Gough, 2015). "Social need" is also described by Sen's capability approach (Sen, 1999) as what people can do from both an individual and social perspective. In other words, what an independent individual needs to be a part of society. In this report, sufficiency is defined as the reduction of energy consumption to a level where benefit is not

[2] https://www.energysufficiency.org/about/undersida/, accessed: 2021-02-20

significantly diminished.

The concept of sufficiency to meet sustainability goals is something beyond efficiency and consistency. While efficiency improves the input-output-ratio and consistency changes production and consumption patterns (e.g. replacing fossil generation with renewable generation), sufficiency aims directly at limiting energy consumption,while still providing energy services that contribute to human well-being in an equitable and affordable way (Darby and Fawcett, 2018). In other words, efficiency is about doing things right whereas sufficiency is about doing the right things (Samadi et al., 2017).

With regard to triggering the behavioral change and spreading energy-sufficient way of living, sufficiency policies should usually take into account two phases: (a) investment phase, meaning that policies target size of products or promote common usage, and (b) the usage phase, meaning that policies promote a more aware usage of services, e.g. shorter travel distances or a lower room temperature in winter (Samadi et al., 2017). Moreover, political instruments to achieve sufficiency can be roughly divided into (a) the modification of individual preference (meaning changing or moving the utility function of humans), (b) providing external incentives in form of a tax and (c) command and control, meaning the implementation of bans and limits (Samadi et al., 2017).

2.2. Relevant literature for sufficiency and energy system modelling

Emphasized by the experts and scientists in the field of sufficiency, Toulouse, Sahakian, et al. (2019) indicate that incorporating sufficiency in energy system modelling and defining quantitative scenarios for it is necessary to provide objective criteria for policy-makers. They also address that related research on sufficiency should be more developed and extended. The areas/sectors with higher priority for research with regards to sufficiency, as indicated by those experts, include mobility, heating and cooling spaces, work and income and finally, food. Grubler et al. (2018) provide a narrative for a low energy demand future that is able to meet the 1.5 ℃ target without relying on negative emission technologies. They also find that increasing the use-efficiency of the energy services has great potential to improve the feasibility of a low-carbon transformation of the supply side. Samadi et al. (2017) give a definition of sufficiency in the energy context as a Greenhouse Gas (GHG) mitigation option, arguing that sufficiency has a large potential to contribute to emission reduction. They review existing prominent energy scenarios and find that most of them do not include sufficiency, concluding that sufficiency in terms of behavioral changes should be included at least in one scenario of energy system models. Moreover, Pfenninger et al. (2014) demonstrate the current status of energy system modelling in application, its transition, challenges and probable potentials for the future policy-making.

One of the main challenges that they address, is how to add the recently-developed concept of demand flexibility and its behavioral aspect, which is at least equally important if not more, in the models.

There have been some studies during the recent years that tried to incorporate sufficiency or demand behavioral changes into the energy system modelling or future energy roadmaps. Using the REMod optimization model, Sterchele et al. (2020) illustrate and evaluate the trajectories towards a carbon-free energy system for Germany until 2050. In their model, they incorporate scenarios that include the related social contexts of sufficiency for the energy transition paths. They have defined six scenarios, two of which represent the energy transition with measures of sufficiency for the years 2030 and 2050. Their results demonstrate that the sufficiency scenario until the end of 2050 has by far the lowest net cumulative expenditures and CO_2 avoidance costs over the period of 2020 to 2050. Although, their study is one of a few which take into account the behavioral changes in energy consumption, their sufficiency scenarios include a single level of demand reduction. Ven et al. (2018) utilize Global Change Assessment Model (GCAM) to incorporate behavioral without initial investments for individuals into the emission reduction scenarios for the EU. Those measures include diet and food consumption, mobility choices and households' treatment. The results of their model demonstrate that modest to strict behavioral change can decrease the CO_2 footprint per capita by 6% to 16%, respectively. Moreover, it can be observed that these behavioral flexibilities are able to reduce the related costs of climate policies e.g. emission trading scheme by a scale from 13.5% to 29.5%. Therefore, policymakers should consider behavioral change as a strong support for emission reduction policies. In order to prepare a roadmap for a smart energy system with 100% renewable energy production in Denmark, Mathiesen et al. (2015) incorporate energy saving scenarios into their model for the years 2035 and 2050. They consider enhanced regulations, behavioral changes, and technical improvements to be the foundation of electricity saving. The results of their model illustrate that a high level of energy savings can reduce the demand for biomass. However, they include both sufficiency and efficiency measures into energy saving measures simultaneously and do not take into account the effect of each separately. Also, they do not mention any clear consideration of sufficiency measures for heat and transport sector. Auer et al. (2020) design four main trajectories for the low-carbon future of the energy system in Europe three of which include behavioral changes in the demand from individuals and communities. They compare these scenarios based on quantitative measures like primary energy demand, installed capacities, electricity generation and annual emission. Yet, they do not specifically focus on sufficient measures of communities.

As noted, none of the previously reviewed studies evaluate the influence of sufficiency in different sectors on the trajectories of energy systems which, as mentioned earlier, can be of utmost importance for the related policies of energy transformation. Nevertheless, the négaWatt Association in France has conducted country-level research and published a scenario for 2050, which also covers consumption reduction through behavioral change (Association négaWatt, 2017). They demonstrate that sufficiency in different sectors can contribute to reducing final energy consumption in 2050 by 60%. In this report, demand reductions in Germany are considered, divided into three sectors: heat, mobility and electricity. The scenarios for each sector are quantified (Section 5) based on the demand reduction potential gathered from related literature which are elaborated in the next section.

3. Quantifying Potential for Sufficiency-based Demand Reductions

In the following section, the concept of sufficiency is used to identify areas where energy demand could be reduced without violating basic human needs. Therefore, demand reduction potentials are quantified based on existing literature in the sectors conventional electricity, heat and mobility.

3.1. Conventional electricity sector

This section analyzes the conventional electricity consumption in Germany and the possible measures to reduce its total demand. The sector includes electricity used for traditional applications such as lighting, information and communication technology (ICT), refrigeration, and mechanical energy. So far, efficiency and consistency have played an important role in reducing the conventional electricity consumption, however, a growing proliferation of appliances, increase in sizes and functionalities, longer usage hours, and new areas of application can be observed (Toulouse and Attali, 2018). This perspective indicates that efficiency and consistency alone will not be enough to achieve climate protection goals, thus societal behavior will play a decisive role in whether and in what form the energy transition can be implemented (Sterchele et al., 2020).

Based on the differences in utilization of electricity and the shares provided in BMWi (2019), the total conventional electricity consumption is distributed between households, commercial spaces and industry (Figure 1). The highest share of electricity in households is used for low process heat (i.e. cooking and baking) and cooling. Also, ICT has a considerable share in electricity consumption. In the commercial sector, most electricity is used for lightning and other appliances, such as PCs. In industry, the use of electricity to operate electric driven-motors and machines dominates the demand. The mentioned partition helps to identify measures in the literature to save a maximum of energy and analyze how much demand reduction these measures could bring.

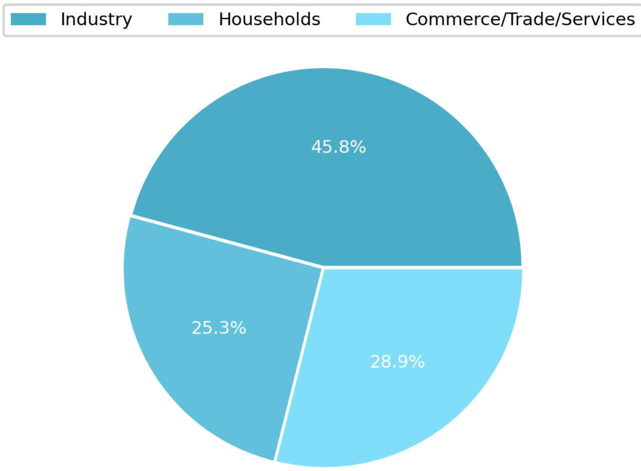

Figure 1: Conventional electricity consumption by sector. Own illustration based on BMWi (2019).

The literature focusing on sufficiency in the electricity sector is scarce. While most of the studies assess the impact of efficient technology on demand, there are fewer studies that evaluate the total potential of sufficiency actions regarding the conventional electricity. As stated in Umweltbundesamt (2015), the main problem that arises in the evaluation of electricity reduction potentials is the partial overlapping of some implemented measures, making it difficult to accurately sum them. As the discussion about the basic needs and wants continues, it is difficult to establish a limit between them in terms of products or the amount of time that the appliances are being used (Toulouse and Attali, 2018).

In this study, a more general approach is followed. The aim is to find literature on different instruments that incite the households, commercial spaces and industry to a behavioral change that would result in a demand reduction. An overview on the instruments and measures applied and their resulting reduction potential found in the literature is provided in Table 1. Instruments are defined as the grouping of measures that differentiate one sufficiency tool to another.

	Instruments	Measures	Reduction	Source
Residential	Behavioral change through intervention	Direct Feedback	5-15%	Martiskainen (2007)
		Direct feedback applications (Europe and N.America)	9%	Zangheri et al. (2019)
		Indirect feedback applications (Europe and N.America)	4%	Zangheri et al. (2019)
		Goal setting	4.50%	Martiskainen (2007)
		Goal Setting with feedback	15.10%	Martiskainen (2007)
		Feedback through smart meters and time-use tariffs (Ireland)	1.80%	Carroll et al. (2014)
		Feedback (peak reduction)	7.80%	Carroll et al. (2014)
		Change of human behavior	20%	Bürger (2009)
	Change in user behavior through intrinsic motivation	Sufficiency in lighting and appliances	15-20%	Umweltbundesamt (2015)
		Change of human behavior	20%	Bürger (2009)
Commercial	Behavioral change through intervention	Group level feedback	7%	Carrico and Riemer (2011)
		Goal setting	12.90%	Nilsson et al. (2015)
		Goal setting with feedback etc.	5.5 and 6%	Nilsson et al. (2015)
	Behavioral change through use of technology	Energy information system + social marketing - feedback (Community Based Social Marketing)	12%	Owen et al. (2010)
	Revolutionary changes through legislations	Four-day week/shorter working time/less production	10.50%	Hansen et al. (2009)
Industrial	Behavioral change through intervention	Energy Audits (Denmark)	7 - 20%	Larsen et al. (2006)
		Energy information system + social marketing - feedback (Community Based Social Marketing)	12%	Owen et al. (2010)
	Revolutionary changes through legislations	Four-day week/ shorter working time/ less production	10.50%	Hansen et al. (2009)

Table 1: Conventional electricity demand reduction measures from literature related to behavioral change.

For households, feedback systems seem to have a considerable effect in motivating households to reduce their electricity consumption. Martiskainen (2007) 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. (2019) 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 a 4% through indirect feedback. Bürger (2009) has conducted one of the few country-level studies that evaluates the maximum achievable decrease in electricity use by "lining up" various sufficiency measures, such as optimizing the usage of different devices and avoiding the stand-by losses. According to Bürger (2009), 20% of electricity could be saved in Germany. A similar approach is used in a study by Umweltbundesamt (2015), which summarizes the energy demand reduction potential by 2030 in several sectors in Germany, including for household appliances.

Energy consumption from non-residential buildings, like commercial offices, is more difficult to assess compared to typical households due to its complex nature (i.e building sizes, varieties of activities and structures or forms). Additionally, an employee mostly shares common equipment with other employees which makes them feel less responsible in conserving energy (Carrico and Riemer, 2011). Yet, there is a huge potential to reduce electricity consumption through sufficiency (Toulouse and Attali, 2018). Also in commercial spaces, a similar approach as in households to incite employees to energy conservation is found in the literature. Carrico and Riemer (2011) and Nilsson et al. (2015) both use the group feedback system and peer education as a tool to change employee behavior and stated a promising 7% and 6% reduction in electricity consumption. Hansen et al. (2009) provided a promising overall energy demand reduction due to several behavioral changes brought by the changing working schedules during the program. Assuming that in the future a 4-days-week work is possible, 10,50% alone could be saved.

As for industrial demand, Banks et al. (2012) and Larsen et al. (2006) 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. (2010) declare a 12% reduction potential through Community-Based Social Marketing (CBSM), such as energy information and feedback systems. Moreover, the 4-days-week work alternative by Hansen et al. (2009) could be partly transferred over to industry, since the office spaces are mostly utilizing the same lighting and equipment as far as conventional electricity is concerned.

3.2. Mobility sector

Following the structure of conventional electricity, this section provides an overview of the energy consumption in the mobility sector alongside with a short literature review of other studies that quantified sufficiency-based demand reductions in the mobility sector. Finally, potential demand reductions through more sufficient behavior are discussed.

Despite increases in energy efficiency in the mobility sector, its energy consumption has been rising continuously since 2010 (BMWi, 2019). To reverse this trend and achieve climate targets, the German Government determined a final energy consumption reduction of 15% to 20% in the mobility sector is required compared to 2005 levels in order to achieve reductions of 60% by 2050 in total energy demand. In the following analysis, mobility demand is split in the sub-categories rail, road and air transport, which are divided again into passenger and freight transport. While rail and road technologies are expected to run with electricity only, air transport demand is fully met by hydrogen.

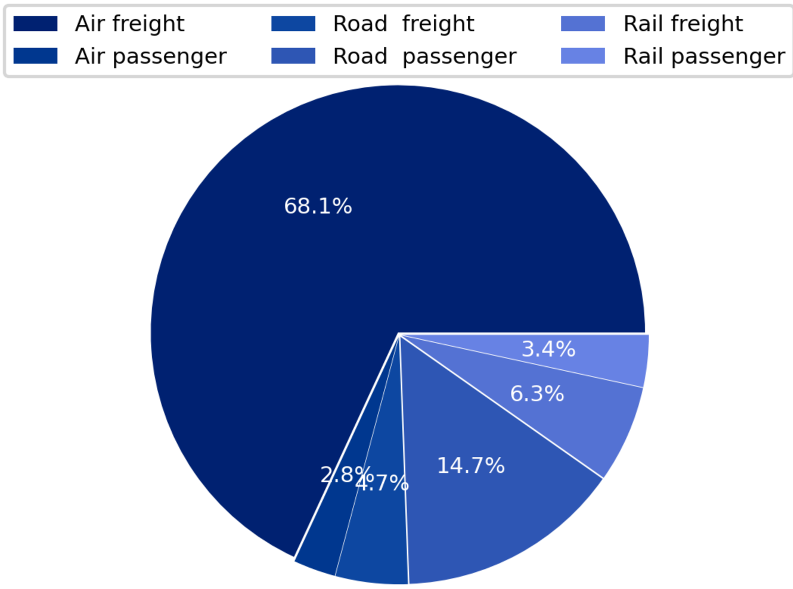

Figure 2: Distribution of mobility. Source: Own illustration based on openENTRANCE[3]
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While there is a growing body of literature on narratives of a future mobility system, little research explicitly investigates demand reductions resulting from different means of transport. Umweltbundesamt (2015) discuss four measures with regards to the transport sector: A modal shift to bicycles, replacing business trips with telemeetings, smaller passenger cars and a reduction of private aviation. Ven et al. (2018) 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 modelled by Sterchele et al. (2020). Two other studies examine the socio-technical transformation of the Danish transport sector, including changes induced by different human behavior (Venturini, Hansen, et al., 2019; Venturini, Karlsson, et al., 2019). Table 2 provides a structured overview on the measures applied in the literature.

[3] Read more about openENTRANCE at https://openentrance.eu/

Measure	Value range	Source
Bicycles		
Modal shift from MIT to cycling	-3.5 to -10%	(Umweltbundesamt, 2015; Ven et al., 2018)
Increased level of investment in bike infrastructure	+50 to +100%	(Venturini, Karlsson, et al., 2019)
Increased share of E-Bikes in total	+1 to +50%	(Venturini, Karlsson, et al., 2019)
Motorized individual transport		
Replacing business trips with telemeetings	-40% to -60%	(Umweltbundesamt, 2015)
Smaller passenger cars through regulation	-7.5%	(Umweltbundesamt, 2015)
Reduction of motorized individual transportation	-30%	(Sterchele et al., 2020)
Reduced commuting demand through teleworking	-1% to -20%	(Ven et al., 2018; Venturini, Karlsson, et al., 2019)
Increased load factor for every commute car trip (carpooling)	2	(Ven et al., 2018; Venturini, Karlsson, et al., 2019)
Public transport		
Modal shift to public transport for all commuting demand	-100%	(Ven et al., 2018)
Reduced traveling time of public transport	-1% to -10%	(Venturini, Karlsson, et al., 2019)
Aviation		
Reduction of aviation	-55%	(Sterchele et al., 2020)
Reduction of private aviation	-50%	(Umweltbundesamt, 2015)
Avoid flights that can be replaced by another transport mode <10h	-25%	(Ven et al., 2018)
Replace intercontinental leisure flights with intra-EU trips	-50%	(Ven et al., 2018)

Table 2: Transport demand reduction measures from literature related to behavioral change.

The following subsections present the sufficiency measures and potential increase in efficiency, structured into road, rail and aviation transport. These measures were identified through research in scientific literature and own assumptions based on grey literature.

3.2.1. Road

Motorized Individual Transport (MIT) is the strongest driver for energy demand in the non-commercial mobility sector. If humans choose to use a bicycle instead of a car for shorter distances, a so-called modal shift, the energy demand for MIT could be reduced by up to 10% (Umweltbundesamt, 2015; Ven et al., 2018). According to the statistics published by the German Ministry of Transport, 18% of MIT is due to commuting to work (BMVI, 2019). Assuming that only 1 day of home office is possible each week, transport demand related to commuting could be reduced by 20% (Ven et al., 2018). A further 19% of MIT is due to business travels (BMVI, 2019). Consequently, transport demand related to business travels could be reduced by 60%, assuming that business trips are gradually replaced by telemeetings (Umweltbundesamt, 2015). Energy demand of MIT 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 have the potential to reduce the energy demand of MIT by 5% (Ven et al., 2018).

The German government stated the aim of reducing energy consumption of the total freight transport in Germany by up to 20% in 2030 which includes both road, rail and air freight transport (Deutsche Bundesregierung, 2016). For short distance between 200-300km road freight transport is extensively being used due to excellent connectivity (Dionori et al., 2015). With rising international trade, it is expected that the ton-kilometers in Germany is likely to rise by 12% by the year 2030 compared to the 2010 levels (BMVI, 2016). The Federal Government also expects a rise of 38% of freight moved and is considering a vast expansion of the existing networks to potentially reduce impacts such as road haulage and environmental emissions. The following sufficiency measures could help reduce large-scale infrastructure expansions of roads and yield climate friendly solutions.

Fuel consumption can be minimized by practicing regular maintenance of the freight fleet. Usage of tire pressure monitoring systems, low friction oil, and low rolling resistance tires vary the fuel consumption in vehicles (Roth et al., 2015). By establishing best practices in operation and maintenance of the freight vehicles the energy demand can be reduced up to 10%. Since drivers play an important role in movement of the vehicles, training on efficient driving can lead to reduced energy consumption. Training in speed regulation of vehicles coupled with other fuel efficient driving techniques can reduce the fuel utilization leading to a reduced energy usage of 10% (Villalobos and Wilmsmeier, 2016). Optimal space utilization can be achieved by developing better packaging solutions. Inappropriate packaging and the need of immediate deliveries and empty trips lead to under- utilization of the available capacity in freight transport. According to a study conducted by Roth et al. (2015), planned packaging to reduce the packaging volume increased the utilized transport capacity by 30%. The measure can include small modifications to product designs and also long term planning leading to significant savings in energy due to reduced trips. Online shopping deliveries are rising astronomically which is evident from the numbers by Statista [4]. In 2019, 30% of the population in Germany shopped online every week. This contributes to the large proportion of the freight transport by road as most deliveries are made by delivery vans around the country. According to reports by Nicole Goebel [5], 12% of the online orders in Germany are returned. This not only has an impact on the revenue for the retailers but also increases a need in transportation of the goods back to the suppliers. Overall, the process of returns and replacements can increase the strain on the road freight systems. Better quality checks for defective items and responsible online shopping has the potential to reduce this number by 50%.

3.2.2. Rail

Rail transport constitutes a smaller share of private transport and sufficiency-based demand reductions follow a similar pattern as private MIT reductions. A modal shift from public transport to bicycles could reduce the energy demand of rail transport by roughly 3% (Greiner and Hermann, 2016). 21% of public transport is due to commuting and 11% of public transport is due

[4] https://www.statista.com/statistics/1086382/online-shopping-frequency-germany/, accessed: 2021-02-19
[5] German online shoppers are serial returners, available at: https://p.dw.com/p/, accessed: 2021-01-22

to business travels (BMVI, 2019). Analogous to MIT, these shares of public transport demand could 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 (Dionori et al., 2015). There are several factors that decide the type of freight transport opted by the shippers which are based on the type of goods carried and the time constraint in hand. However, above distances of 300km train freight transport is extremely competitive in terms of cost. Since 1994, the development of the railway infrastructure in Germany has been slower than the road infrastructure. The regulations in Germany currently support air and road transport in terms of taxation which has led to the slow growth of the sector. However, the German Government has identified the potential of the trains in moving freight to reduce the CO_2 emissions, as it is one of the lowest amount of GHG emissions per ton-km (Donat, 2020).

Train speed control during operation has one of the highest potential for reducing energy use. Controlling parameters such as acceleration, cruising and coasting can yield better engine performances which develops optimal driving regimes. This can be facilitated by using continuous traction control systems which utilize the principles of optimization using numeric algorithms. Several algorithms have been developed such as Particle Swarm Optimization and Artificial Neural Networks with various objective functions. Minimizing energy usage has been a part of most of these algorithms and is capable of decreasing the present energy consumption by rail between 20-30% (Corlu et al., 2020).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 on rail infrastructure and expansion planning based on time table intervals coordination (Donat, 2020). Such optimization algorithms have the potential to reduce energy demand in rail freight scheduling by up to 14% (Corlu et al., 2020).

3.2.3. Aviation

In this Section, reduction measures for freight and passenger air transport that will be implemented in this study are explained. First passenger transport is analyzed followed by freight transport.

Up to 60% of passenger flights in Germany will be related to business travel in 2030, according to Umweltbundesamt (2015). Given the rise of COVID-19, and thus the move of essentially all business meetings online, a future is imaginable in which most business meetings between entities in different locations occur online. The annual flights report for 2020 of the Fraport

AG for Germany's biggest airport located in Frankfurt (Main) showed a reduction of 86.5% of all business flights, compared to 2019 (Fraport AG, 2021). Furthermore, the well-developed infrastructure and the technological progress in today's train traffic allow the replacement of national business flights by rail if they are unavoidable. The location of main stations for trains in city centers and the absence of security checks before traveling can lower the difference in travel time between flights and trains significantly. Saving an enormous amount of energy at the same time and benefit of around 61% renewable electrification of the rail system in Germany (Deutsche Bahn AG, 2020).

Data analysis of EUROSTAT[6] show that the average amount of passenger flights in Germany diminished by around 71% in the first three quarters of 2020 in comparison to the previous due to COVID-19. The trend for the last quarter of 2020 has been extrapolated with help of the annual report for 2020 of the Fraport AG as it related very well to the EUROSTAT data (Fraport AG, 2021). A total decrease of about 74% was calculated for passenger flights in 2020, including starts and landings in Germany. On average 33.8% of all German flights are intercontinental and 56.1% to other European countries (Fraport AG, 2020). Assuming that flight behavior in Germany will change towards more sustainability, the private flight rate of 2020 was taken as basis for the scenarios in this study. Excluding the business flights rate for 2035 from the total decrease, a decline of 54% in private air traffic for 2035 is calculated. As the flight reduction rates in 2020 were similar for intercontinental and intra-european flights (75.3% and 72.3%, respectively) (Fraport AG, 2020), an energy reduction according to the reduction of flights is assumed. Intra-european, this and higher reduction rates can be reached by replacing flights by train journeys. Replacing almost all intra-european flights in that way, the measure could compensate for possible increases of intercontinental flights.

Plans to replace kerosene fueled planes by hydrogen fueled ones is a big step forward regarding CO_2 emissions reduction, provided the hydrogen is not produced with fossil resources (BMVI, 2018). Nevertheless, air traffic has a high energy demand compared to other mobility technologies. Taking the increasing freight traffic into account it is very unlikely, that there will be a significant energy demand reductions from decreasing freight in the future, including cargo flights (Umweltbundesamt, 2019). Nonetheless, huge energy savings are possible in this transport method and will be demonstrated in the following. In 2019, 22% of all cargo flights to and from Germany were continental flights (EU-27)[7]. A ton of freight that is transported by train instead of plane currently consumes more than 90% less energy. The energy consumption per

[6] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=avia_paoc&lang=en, accessed: 2021-01-28
[7] https://ec.europa.eu/eurostat/statistics-explained/index.php/Air_transport_statistics#Progressive_growth_\in_air_transport_of_passengers_in_the_course_of_2019, accessed: 2021-02-01

ton of freight for ships is even lower (Own calculations based on [8], [9]. Assuming that in 2035 all continental and national freight flights are replaced by ships and trains, energy savings of 20% in air freight transport related to Germany could be achieved. Expanding this measures to 10% of intercontinental flights, around 30% of energy could be saved.

3.3. Heat sector

The heat sector is responsible for 54% of the overall energy demand. This reflects the importance of possible reduction potentials which are investigated in the following paragraphs. The heat sector is then further subdivided into residential and commercial heat demand representing space heating and domestic hot water demand, which is fully supplied by heat pumps, as well as the process heat demand representing the industrial energy demand. Process heat has three categories reflecting on the respective temperature level in the industry branches as outlined in Section 3.3.2. The researched measures and their potentials are summarized in Table 3 and further explained in the upcoming sections.

Measure	Value range	Source
Space heating demand		
Lowering average room temperature by 1-2℃	-4.4% to -9%	(Umweltbundesamt, 2015; Marshall et al., 2016)
Turning down thermostat by 1℃	-13%	(Palmer et al., 2012)
Decreasing living space per person	-24.9% to 35.7%	(Bierwirth and Thomas, 2019b)
Hot water consumption		
Water efficient shower heads	-50%	(Palmer et al., 2012)
Feedback system about showering time	-5% to -10%	(Toulouse and Attali, 2018)
Shorter and less frequent showering	-20% to -30%	(Palmer et al., 2012)
Adjusting water consumption	-70%	(Lehmann et al., 2015)
Process heat low temperature		
Decreasing food waste	8.6% - 13.2%	(Schmidt et al., 2019; Vita et al., 2019)
Process heat mid temperature		
Increasing plastic recycling	1.4% - 2.1%	(Umweltbundesamt, 2021; Chemischen Industrie, 2020; Association négaWatt, 2018)
Extending useful life of products and	3% - 8.2%	(Prakash et al., 2016)
establishing service-based sharing economy	-	(Vita et al., 2019)
Modal shift construction products and	0.67% - 1.7%	(Hertwich et al., 2019; Bundesverband Baustoffe – Steine und Erden, 2019)
reduced construction materials	-	
Process heat high temperature		
Modal shift construction products and	3% - 7.6%	(Hertwich et al., 2019; WV-Stahl, 2020)
reduced construction materials	-	

Table 3: Heating demand reduction measures from literature related to behavioral change.

3.3.1. Residential and commercial heating demand

As of 2019, space heating accounts for a share of 26.34% of the total end-energy consumption[10]. As can be seen in Figure 3, more then 70% of the energy used for space heating in Germany is currently covered by non-renewable sources like natural gas, oil and coal.

[8] https://ibir.deutschebahn.com/2019/de/konzernlagebericht/oekologie/klimaschutz/unser-klimaziel-halbierung-der-treibhausgasem accessed: 2021-02-24

[9] https://modernairliners.com/boeing-747-8/boeing-747-8i-and-8f-specs/, accessed 2021-03-05

[10] https://www.bmwi.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html, accessed: 2021-01-31

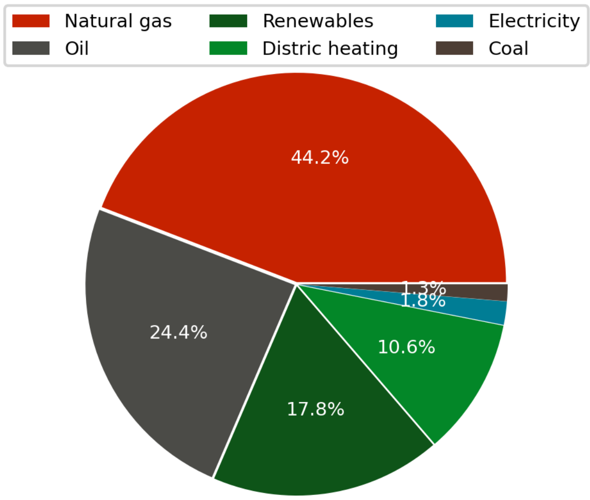


Figure 3: Residential space heating by energy source for Germany 2018. Own illustration based on AGEB Statista 2021[11]

The substitution methods explained above lead to the fact that the demand for electricity will increase enormously in interest of the decarbonization goals. The paper addresses this additional electricity consumption by applying sufficiency assumptions in parallel to creating a sector coupled energy system.

Literature that states potential in energy saving through a lower average room temperature in buildings is introduced in the following. The average room temperature for Germany's households in 2019 is 19.6 °C[12]. Nevertheless, a reduction of one degree is acceptable without diminishing the living comfort. The often cited "6% rule" implies that the reduction of 1 °C lead toward 6% a energy saving. However, deviations from this rule are to be assumed, in case of rising amounts of low-energy houses. The Umweltbundesamt declares in a concept paper potential from 4.4% to 9% in 2030 by reducing the temperature by 1 or 2 °C, taking into account the refurbishment rate in Germany (Umweltbundesamt, 2015). A report from Cambridge Architectural Research investigates within a model based research the energy saving potential of small changes in household behavior. They quantify a reduction potential of 13% of the space heating energy by turning down the thermostat by 1 °C (Palmer et al., 2012). Marshall et al. (2016) calculate energy savings considering four different measures for three different occupancy patters. Energy savings of 9% are achievable by reducing the households space Temperature by 1 °C.

[11] https://de.statista.com/statistik/daten/studie/250403/umfrage/raumwaermebereitstellung-nach-energietraeger-\ in-deutschen-haushalten/, accessed: 2021-01-25
[12] https://de.statista.com/statistik/daten/studie/584871/umfrage/raumtemperatur-in-mehrfamilienhaeusern-nach-\ raumart-in-deutschland/, accessed: 2021-03-06

Regarding domestic hot water consumption, two influencing factors are conceivable, technically actions or change in behavior. For instance, the installation of water efficient shower heads can save up to half of the energy usage for showering (Palmer et al., 2012). This action only takes place once and does not change the consumer behavior in a long term perspective. Additionally, a 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 frequency showering. Toulouse and Attali (2018) experienced an average cut of 5-10% in energy usage which emerges from the feedback about showering time. As stated by Lehmann et al. (2015), the demand of hot water in households can be simply reduced by shortening the daily shower time and adjusting the water consumption with water saving fittings up to 70%.

Bierwirth and Thomas (2019b) argue, in an extended extract of their published concept paper about sufficiency in buildings (Bierwirth and Thomas, 2019a), that the European trend of increasing living space per person creates high demand for energy along with societal effects. They focus on the balance between what floor space is needed for a decent living and what is too much. The average living space 2018 in Germany is 46.7m^2 per person[13]. Taking into account five different sizes of households, Bierwirth and Thomas (2019b) calculate a "adequate" average space of 32.3m^2 per person. Consequently an energy saving potential of 24.9% (35m^2/cap) to 35.7% (30m^2/cap) are achievable for the space heating. Associated reductions of energy service demand related to lightening and building material are not included and would lead to even more saving potentials. Compared to other European countries, energy sufficiency potential of Germany is rated as "very high" and is only surpassed by Luxembourg (Bierwirth and Thomas, 2019b).

3.3.2. Process heat

It is becoming increasingly evident that a systemic change in the use of energy services is required, as current economic growth highly depends on the industrial energy throughput. Commonly, the solution of degrowth was established to achieve a reduction in energy demand by reducing the overall consumption and thereby production level of a society as well, challenging the traditional thinking of continuous economic growth which is considered unsustainable (Robra et al., 2020; Sandberg et al., 2019). To achieve such consumption reductions, certain sufficiency measures can support this development, but placing the responsibility solely on the consumer will not have the desired scale effect and therefore needs to aim at including the interconnected production side as well. Modal shifts occurs as emission free consumption where energy intensive materials and products are substituted by less energy intensive

[13] https://www.destatis.de/EN/Themes/Society-Environment/Housing/Tables/average-living-floor-space-per-person-germany.html, accessed: 2021-02-15

products (Vita et al., 2019). This inclusion can be versatile and is investigated in the upcoming parts. Accurate estimations of sufficiency measures in the industry sector regarding the demand of process heat are yet to be developed and verified. Thus, qualified assumptions and correlations of various institutional and governmental studies are used to determine the extent to which a demand reduction could be realized in a simplified system where the import and export of goods is neglected. The subdivision of the prospective process energy demand in each industry branch is carried out by Auer et al. (2020) and serves as the baseline demand without the implemented sufficiency measures as shown in Table 4. Additionally, it is assumed that each measure only affects its respective industry sector without any linkage to other branches to avoid double counting. The entire process heat demand consists of 12.24% low temperature, 60.41% mid temperature and 27.35% high temperature demand which is classified with each temperature level and their respective branches in Table 4.

Temperature	Food	Paper	Chemical	Engineering / Manufacturing	Refineries	Other	Non-metallic / Minerals	Iron / Steel	Non-ferrous / Metals
Low: < 100℃	48.96%	51.04%	0	0	0	0	0	0	0
Mid: < 500 ℃	0	0	41.33%	20.55%	12.44%	12.27%	13.41%	0	0
High: > 500 ℃	0	0	0	0	0	0	0	85.90%	14.10%

Table 4: Process heat demand share of industry branches. Source: Own illustration based on openENTRANCE[14]

Reduction of low temperature process heat demand

Decreasing food waste from 35% to 17.5% per year could already be achieved according to Schmidt et al. (2019), which functions as the key study for Germany's food waste strategy by the Federal Ministry of Food and Agriculture. Thereby setting this aim as a low ambition for food waste reduction. This loss of produced goods occurs along the entire value chain, where households responsibility account for slightly above 50%. Sorting losses due to appearance defects are not considered yet and could thereby further increase the energy saving potential in the food industry (Steffen Noleppa, 2015). Adapting an ambitious measure with a limit of food consumption to 2586 kcal/day, leads to a reduction of 27% of the entire food intake where the consumption is reduced by the average surplus calories consumed in Europe (Vita et al., 2019). According to the underlying energy demand study, the food industry makes up 49% of the low process energy demand corresponding to a demand reduction with the Low ambition measure of 8.6% and 13.2% as a High ambition scenario, where the loss and energy intensity is assumed to be even in all food product categories.

[14] More can be read about openENTRANCE project at https://openentrance.eu/

Reduction of mid temperature process heat demand

Additional reduction of overall waste accumulation for various material groups can be achieved by increasing their respective recycling efforts. Especially plastic materials are primarily incinerated instead of returned into the material flow, also due to its pollution where behavioral change of feeding cleaner plastic back to waste treatment facilities can have a positive impact. According to Umweltbundesamt (2021), the recycling rate for plastics only amount to 47% whereas the rate for paper and metal products are 75.9% and 92% respectively. Here, all plastic exports are counted as recycled which incorporates uncertainty. That's why the adjusted recycling rate drops to 17.3% of the reused recycled material in new plastic products Conversio GmbH, 2018. The potential of plastics being recycled to a similar amount as paper is 30% to 60% even though it would require a higher material unity and recyclability to achieve the upper end of the potential which has already been implemented in the European plastic strategy with the action plan to transform towards a circular economy (European Commission, 2020). That's why an increase by 45% and equivalent substitution of virgin material is assumed as a high ambition and 30% as a low ambition. The plastic production is incorporated in the chemical industry sector which accounts for a share of 12.6% of its overall production index (Chemischen Industrie, 2020). As a simplification, the energy intensity is uniformly distributed among all products in the chemical industry requiring a mid temperature process heat demand of 41.3%. When using recycled plastic material instead of virgin material in the plastic material stream, 90% of the required energy demand can be reduced (Association négaWatt, 2018). This measure leads to an overall reduction potential of 2.1% of the mid temperature process heat demand when following a High ambition and 1.4% as a Low ambition.

One of the key sufficiency strategies mentioned in many studies is an extended product lifetime (Umweltbundesamt, 2015; Wieser, 2016). As this is aimed at reducing the consumption of consumer products, different kinds of obsolescence have to be considered and overcome to realize the extended useful life (Prakash et al., 2016). The need of economic growth effected a continuous decrease of product longevity and thereby an unsustainable material and energy input. When facing product defects, general repair possibilities are hindered due to complicated component integration or unavailable replacement components. Software obsolescence occurs after updates are only available for new models, forcing the consumer to abandon still functioning products. These are mostly factors which are influenced by the producer. Nevertheless, psychological obsolescence occurs at the consumer side with a desire of owning the newest models or using newly developed functions, thus significantly decreasing the primal useful life of a product with at least 10% between 2004 and 2013 for all major appliances besides laptops (Prakash et al., 2016). When evaluating precisely, this is also enforced by marketing efforts of the producer. Creating a sustainable market with extensive product longevity could be fostered by introducing a statutory warranty and increasing the already implemented defects liability of only two years as stated in § 438ff German Civil Code. Replacing large household appliances due to a defect within 5 years has increased from 3.5% to 8.3% and between 6 and 10 years from 16.7% to 18.3% of all replacement acquisitions. The overall acquisitions made because of defects amount to 55.6%. Implementing a statutory warranty of 5 years and setting the defects liability to 10 years would nearly eliminate this type of early replacements and save at least 14.8% of produced products. Additionally, regulating a mandatory availability of components for at least 20 years would ensure prospective repairability, which is already practiced by the most sustainable companies, achieving even greater longevity. When assuming a similar substitution quota for all product categories, this would lead to a reduction of at least 14.8% of the manufacturing/engineering energy demand even though it would have a significant scale effect in other product categories such as smartphones, which are typically replaced within 2.5 years. This is incorporated with a share of 20.5% in the mid process heat demand, leading to a total reduction of 3%. Thereby the efficiency effect of new machines is not considered but was also not recognized as relevant when compared to a significantly extended useful life (Prakash et al., 2016).

Another way to decrease consumer product consumption is by supporting consumption communities, such as shared washing facilities in multi-family houses. Consumption communities or shared economy can be applied to all kinds of product categories, decreasing the rate of product ownership as is already occurring in car transportation. This way repair obstacles could be overcome when producers engage in service based business models and replacement can be simply restricted to a useful life of at least 10 years. Thereby, certain product categories which are effected by functional and psychological obsolescence by the consumer could increase their useful life as well and reduce the overall energy demand of its production. In the summary of sufficiency measures conducted by Vita et al. (2019) and their respective assumptions, a consumption reduction of 50% is assumed for a repair and share scenario, where 10% will be shifted to services. The spread of 40% implements the upper limit in the manufacturing / engineering energy demand reduction potential as the ambitious scenario of 8.2% in this study.

Reduction high temperature process heat

Enforcing a modal shift in the construction industry where current materials such as steel and cement are replaced by wooden structures can have a significant impact in the reduction of the industrial energy demand as the iron/steel production makes up 86% of the high process heat demand. According to Hertwich et al. (2019), 10% of all construction materials can be replaced by wood already. The share of steel produced for the construction industry makes up 35% in 2020 which would lead to an energy demand reduction potential of 3% regarding the high process heat (WV-Stahl, 2020). Due to the tremendous difference in energy intensity of the lumber production compared to steel production, it is assumed to be energy neutral. Additionally, cement production has a large share of energy demand regarding construction materials, making up 50% of the subsector of non-metallic minerals which account for 13.4% of the mid process heat demand (Bundesverband Baustoffe – Steine und Erden, 2019). As no other measure is implemented within this branch, double counting will be avoided and the reduction potential of 0.67% of the mid process heat demand can be added. This potential is considered to be the Low ambition scenario.

When implementing the sufficiency strategy of reducing the average floor space per capita in the residential/commercial heating mentioned in 3.3 by 30%, a similar reduction in construction materials will occur due to the reduced demand in living space. As 10% of the materials are already substituted in the measure before, it can only be applied to 90% of the material production. The occurring construction volume for residential buildings amounts to 57.1% of all construction activities in 2017 and it is assumed that the demand of materials are the same for all types of construction projects (Bundesverband Baustoffe – Steine und Erden, 2019). This leads to a reduction potential of 4.6% of the high process heat demand when observing the steel production and 1.03% of mid process heat demand when decreasing the cement production accordingly. The ambitious scenario is reflected by the combination of the previous measure and the present measure when added to their respective temperature levels.

4. Methodology and Data

The following section presents the methodological framework needed to simulate a capacity expansion model for a 100% renewable energy system scenario in Germany by 2035. First, the chosen modeling tool is introduced along with its corresponding attributes and constraints. A reference case, to which further reduction assumptions will be applied, is also presented. Second, the mix of renewable technologies including generation, storage and conversion assets are described. Finally, the demand data used for this research is explained as well as its associated sector share.

4.1. Model description

For the purpose of this study, a cost-minimizing model provided by AnyMOD framework is used. AnyMOD is a graph-based framework that facilitates modeling high levels of renewable resources and sector integration (Göke, 2020a). Besides these, the AnyMOD framework provides the ability to define the level of temporal and spatial parameters for each energy carrier and technology as needed. For instance, the supply and demand of electricity can be balanced hourly, while hydrogen balance can be set to daily resolution. This approach, on one hand, reflects certain flexibilities inherent to the energy system and on the other hand, leads to a noticeable reduction of the model size. The framework itself and the documentation to facilitate its practical application are openly available[15].

The model's objective consists of capacity expansion costs and energy system operating plus variable costs. There is a list of predefined parameters for the set of carriers and technologies in the model which are used to assign value to them in order to create the desired energy system. The model's constraints ensure that the hourly demand for each carrier in each sector is fulfilled. In this regard, the required capacity to expand, generate, store and transport the energy in all sort of available carriers and technologies are calculated separately.

Based on this model, a baseline energy system for Germany is designed which is referred to hereafter as the "reference case". In this energy system, electricity is the primary energy carrier which is transformed to hydrogen and synthetic gas as secondary energy carriers. All required energy is generated by 100% renewable technologies (see Section 4.2) and after running the model, the optimal capacity of these technologies are calculated in order to meet total demand (see Section 4.3) in each period. Imports and exports of energy were not included in the model, as the focus is on the impact of demand-side changes. Without explicitly modelling neighboring countries, which exceeds the scope of this research, imports cannot be guaranteed to be fully renewable as well. The approach to omit import and exports when analyzing fundamen-

[15] The link to the corresponding repository is: https://github.com/leonardgoeke/AnyMOD.jl

tal trade-offs in renewable systems was adopted from previous research (Schill and Zerrahn, 2018).

The flow diagram of the reference case is presented in Figure 4. The optimal capacity expansion of each technology is depicted in a qualitative format in this diagram. The dummy variables "heat", "mobility" and "conventional demand" were included in the simulation as "end-users" to characterize the aggregated capacity expansion of the included technologies per sector. As it can be seen, a minority of the heat demand is supplied in the forms of synthetic gas and hydrogen, while the majority of the mobility demand is met by hydrogen.

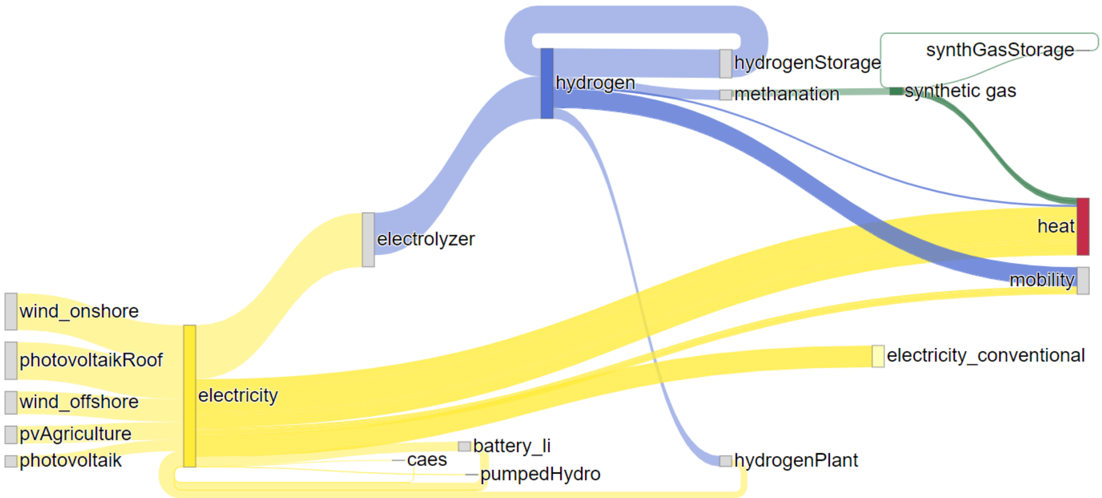


Figure 4: Qualitative energy flow diagram for reference case

4.2. Renewable technology

The modelled technologies are split into two categories, conversion technologies and storage technologies. The conversion technologies convert energy from one form to another (an electrolyzer converts electrical energy to chemical energy), or generate energy (such as wind or solar). The following conversion technologies are included in the model input parameters: rooftop photovoltaic, open-space photovoltaic (ground-mounted), agricultural photovoltaic (solar panels mounted above partial shade crops), on-shore and off-shore wind, hydrogen plant, electrolyzer, and methanation. The costs assumed for capacity expansion for these technologies is taken from projections made by Kost et al. (2018) (photovoltaic rooftop/open space and wind), Trommsdorff (2020) (agricultural PV), and Göke et al. (2019) (electrolyzer and methanation), as seen in the Appendix (Table A.1).

The capacity limits for onshore wind and solar are split into six regions of Germany (East, West, Northeast, Northwest, Southeast, and Southwest) on an hourly basis for an average year. The offshore wind capacity is treated as one region, and similarly is on an hourly basis for one year. The capacity assumptions are derived from openENTRANCE[16], with the exception of agricultural PV, which is derived from Trommsdorff (2020). These are visualized in Figure 5.

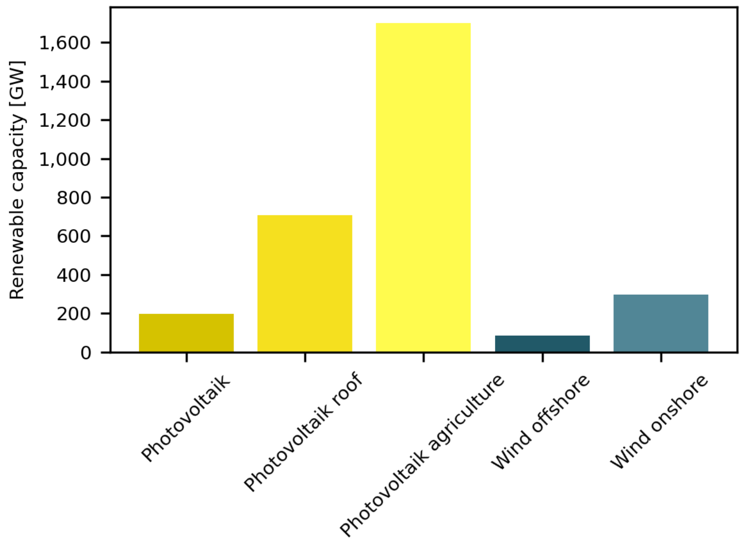


Figure 5: Renewable potentials of the model

The following storage technologies are included in the model: Li-ion batteries, CAES, pumped hydroelectric storage (involving two reservoirs of different elevations, water is pumped during periods of excess supply and water is released during times of demand, recapturing the energy), synthetic gas storage, and hydrogen storage. The price assumptions for these technologies are taken from Kost et al. (2018). Figure 6 visualizes the interactions between the different forms of energy in AnyMOD.

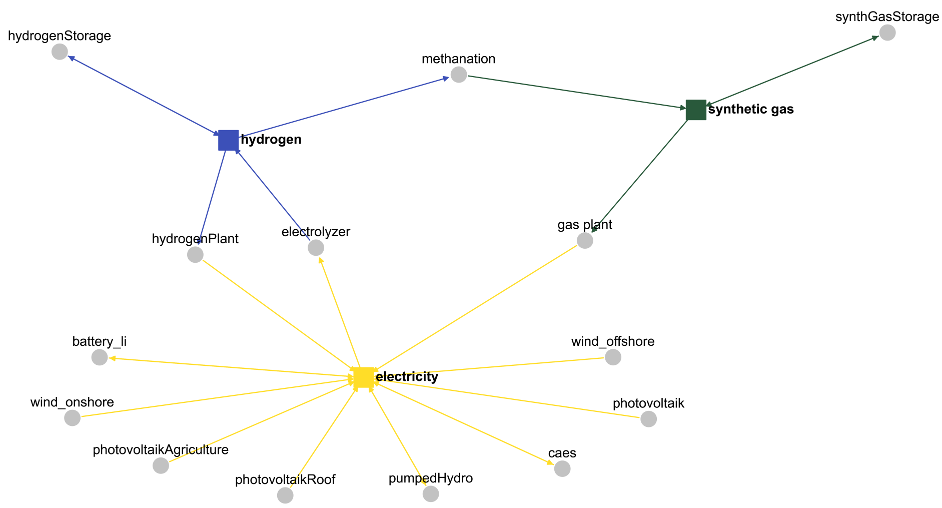


Figure 6: AnyMOD Energy Flow Graph

[16] More can be read about project at https://openentrance.eu/

4.3. Demand data

Demand data is taken from the openENTRANCE project, which develops scenarios compliant with the Paris Agreement Auer et al. (2020). The scenario chosen is called „societal commitment“ and aims for a strong change of behavior towards a sustainable lifestyle. Even before applying our sufficiency measures, energy demand is reduced from a reference scenario for transport and delivering services, combined with energy advantages of intense digitalization and first steps towards a circular economy[17]. Demand in societal commitment is lowered consistently across all sectors, with additional demand shifting from the residential sector's peaks. Data has been cross-checked and is consistent with other publications, notably the SET-NAV project (Auer et al., 2020).

The demand data given refers to primary energy. Sectors consist of different technologies, which can be assessed independently. Measures can reduce the total energy or flatten specific periods by altering the load curve profile. Data is gathered for the sectors of mobility, heat and electricity. In Figure 7, the demand curves of all sectors are shown.

The sectors mobility and heat have sub-categories attached. For example, the mobility sector has categories for rail, road and air mobility in combination with passenger transportation and freight transport. Sufficiency measures can be applied up to an hourly resolution. Summing up all sectors and categories, the reference load profile has some sharp peaks but is within the expected range (Figure 7).

[17] The demand data from 2050 is taken to get a fully renewable scenario. It should be shown how to improve a renewable scenario with sufficiency measures, and therefore it is not essential when this is.

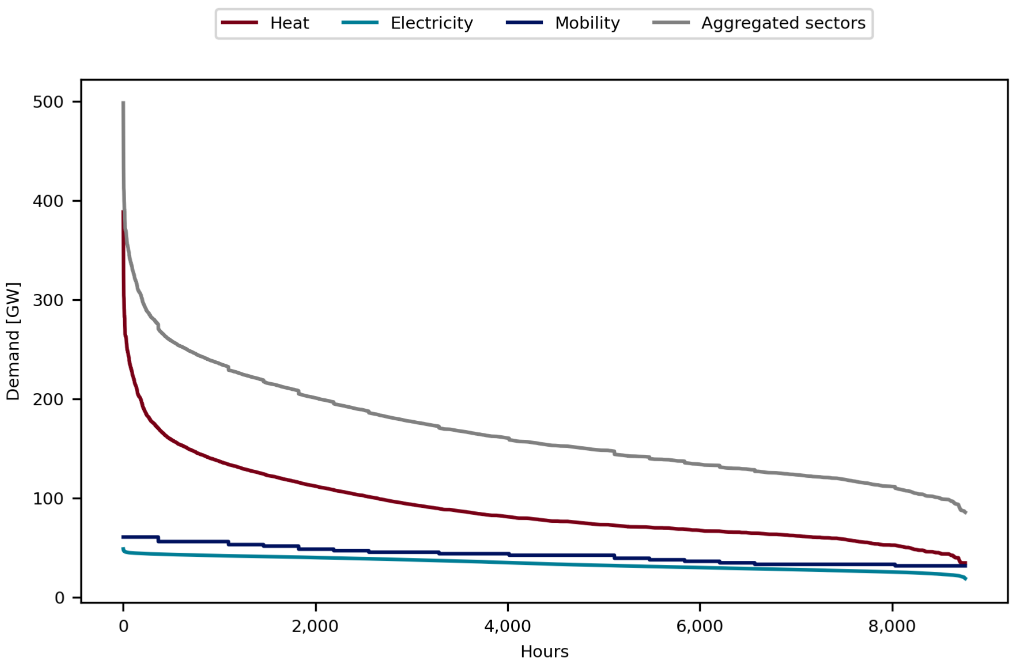


Figure 7: Load profile: All sectors and reference case

5. Sector-specific Scenarios

After quantifying the potential for sufficiency-based demand reductions in Section 3, sector-specific scenarios with the corresponding assumptions in conventional electricity, mobility and heat sectors are developed in the following subsections.

5.1. Conventional electricity demand reduction

The electricity sector is divided into a Low and High Ambition Scenario and derived from the reduction potentials in residential, commercial, and industrial demand presented in Section 3.1. Table 5 below summarizes the potential reduction in each demand and the total conventional electricity sector. Under the Low Ambition Scenario, a combined reduction of 5.8% is considered, with the industrial electricity demand having the highest reduction potential. Meanwhile, the High ambition scenario represents a promising 19.9% combined reduction, with commercial electricity demand representing the highest relative reduction and industrial with the highest absolute reduction.

Scenario	Sufficiency Impact	Residential (25.3%)	Commercial (28.9%)	Industrial (45.8%)	Total conventional electricity
Low Ambition	Percentage Reduction	4%	5.50%	7%	5.8%
High Ambition	Percentage Reduction	20%	23.40%	17.50%	19.9%

Table 5: Saving potential in Low and High Ambition scenarios for residential, commercial and industrial conventional electricity demand. Percentages in the column headings refer to the share of the sectoral demand.

Figure 8 illustrates the absolute residential, commercial and industrial demand reductions in the Low and High ambition scenarios. The initial conventional electricity demand of approximately 300 TWh is reduced by 18 TWh in the Low Ambition Scenario and 60 TWh in the High Ambition Scenario.

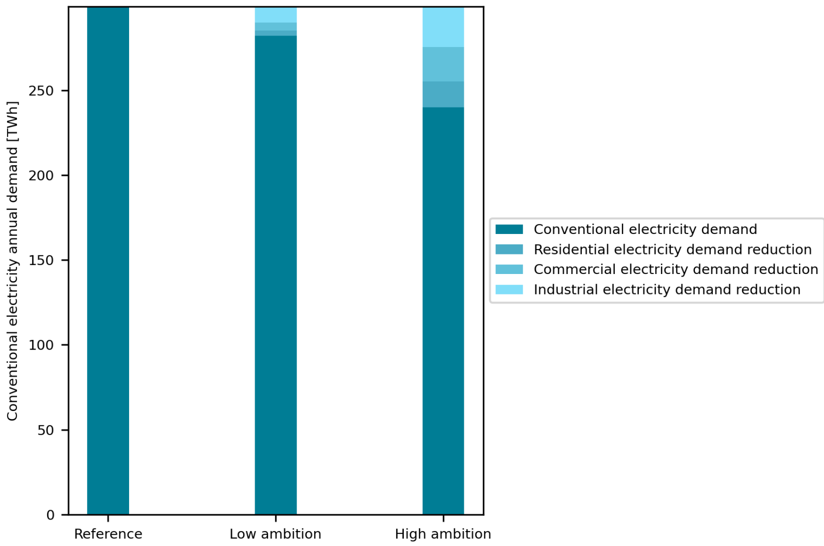


Figure 8: Impact of sufficiency measures on the demand of the conventional electricity sector. Own illustration.

5.2. Mobility demand reduction

Mobility demand reductions are implemented as Low and High Ambition scenarios as well. The reductions are chosen based on the quantified potential as discussed in Section 3.2 for each sub-category of the demand data. Table 6 summarizes the reductions assumed in the sub-categories air, road and rail. A detailed overview on the individual measures in each sub-category with the associated reductions is provided in Table A.2 in the Appendix.

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

Table 6: Demand reduction potential in Low and High Ambition scenarios for air, road and rail mobility demand. Percentages in the column headings refer to the share of the sectoral demand.

The absolute demand reductions resulting from the Low and High Ambition scenario reductions are depicted in Figure 9. The initial mobility demand of approximately 375 TWh is reduced by 81 TWh in the Low Ambition Scenario and 115 TWh in the High Ambition Scenario.

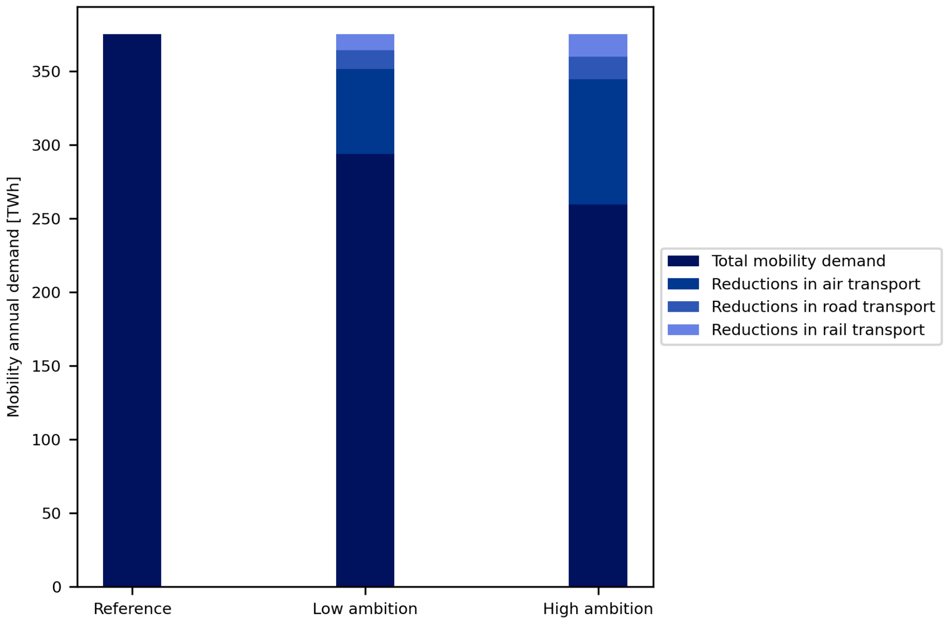


Figure 9: Impact of sufficiency measures on the demand of the mobility sector. Own illustration.

5.3. Heat demand reduction

The heating sector is divided into two parts, which are addressed in separate scenarios due to varying applicability of behavior change assumptions. In a third scenario, the load shifting potential of the private heating sector is evaluated. To combine those different analyses, the final scenario includes the private, commercial and industry sufficiency assumptions (Section 5.3.4).

5.3.1. Private and commercial heat scenario

In contrast to the other sectors, the residential heating demand has extensive peak load hours caused by seasonal differences (Figure 7). Therefore this sectors will be evaluated in stages, instead of in a Low and a High ambition scenario.

Within this scenario, in each stage, different assumptions in behavior change are applied to evaluate impacts of the heating demand in the building sector. In Stage 1, the demand is reduced by 5.01% mainly caused by lowering the average room temperature in private households. In the Stage 2, a total energy reduction of 10.08% is assumed in view of domestic hot water saving potential. Subsequently, in Stage 3, the floor space per capita is reduced which lead to a total reduction of 19.44% up to 34.21%. The detailed literature basis for those assumptions is given in Section 3.3. An overview of the stages is visualised in Figure 10 and in Table 7.

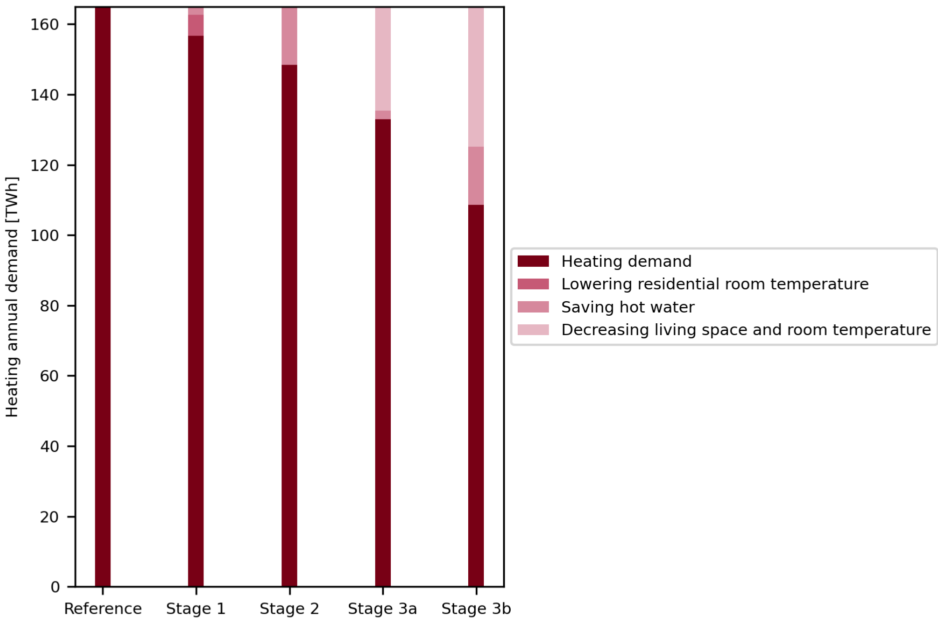


Figure 10: Impact of sufficiency measures on the demand of the residential and commercial heat sector. Own illustration.

	Space heating (household)	**Hot water** (househould)	**Space heating and hot water** (commercial)	**Total savings** in percent of total heat demand
Reference	0%	0%	0%	0%
Stage 1	6%	10%	0%	5.01%
Stage 2	0%	70%	0%	10.08%
Stage 3a	6% + 25%	10%	0%	19.44%
Stage 3b	6% + 35.7%	70%	0%	34.21%

Table 7: Saving potential of private and commercial heating demand caused by sufficiency measures in percentage of total heating demand. Sum of saving potential in space heating household (excluding intersection): 3a: 29,5% savings; 3b: 39,56%.

5.3.2. Process heat scenario

When summarizing all investigated sufficiency measures regarding industrial process heat, aggregated to Low and High ambition scenarios, the following configuration in Table 8 is assumed. The Low and High Ambition Scenarios regarding the low process heat demand focus on reducing food waste and restricting the nutrition consumption to the recommended level, amounting to 8.6% or 13.2%. The varying ambition scenarios of mid process heat are an aggregated combination of increased plastic recycling efforts, further establishing a sharing economy and extending the product lifetime; as well as a reduction of cement utilization in the construction sector due to modal shift and decreased living space as outlined in Section 3.3.2, amounting to either 5.07% or 12%. The high process heat demand reduction only reflects the reduction of iron and steel production due to a modal shift and decreased living space in the construction sector amounting to either 3% or 7.6%. These measures are applied to the respective temperature level and combine to a total demand reduction of 4.9% in a Low Ambition Scenario and 10.9% in a High Ambition Scenario.

	Process heat low temperature	Process heat mid temperature	Process heat high temperature	Total demand reduction
Low ambition	8.60%	1.4% + 3% + 0.67%	3%	4.9%
High ambition	13.20%	2.1% + 8.2% + 1.7%	7.60%	10.9%

Table 8: Saving potential of industrial process heat demand according to the examined measures.

5.3.3. Load shifting potential of heating demand

Due to the seasonal dependency of heating demand, the load profile shows significant peaks during the winter months. This scenario investigates the effect load shifting has on storage and expansion capacity. The total heat demand is not reduced, rather it is allowed to cover the private and commercial demand within 4 (LS4) or 24 hours (LS24) instead of forcing an hourly resolution. Process heat demand follows a pattern and varies between 0 and approximately 60 GW, while the private and commercial heating demand has sharp peaks in limited hours. Considering these different profiles and the fact that building structures have thermal inertia, only the load shifting potential of residential and commercial heat demand is evaluated. Figure 11 shows changes of the load profile with regard to the different demand resolution requirements.

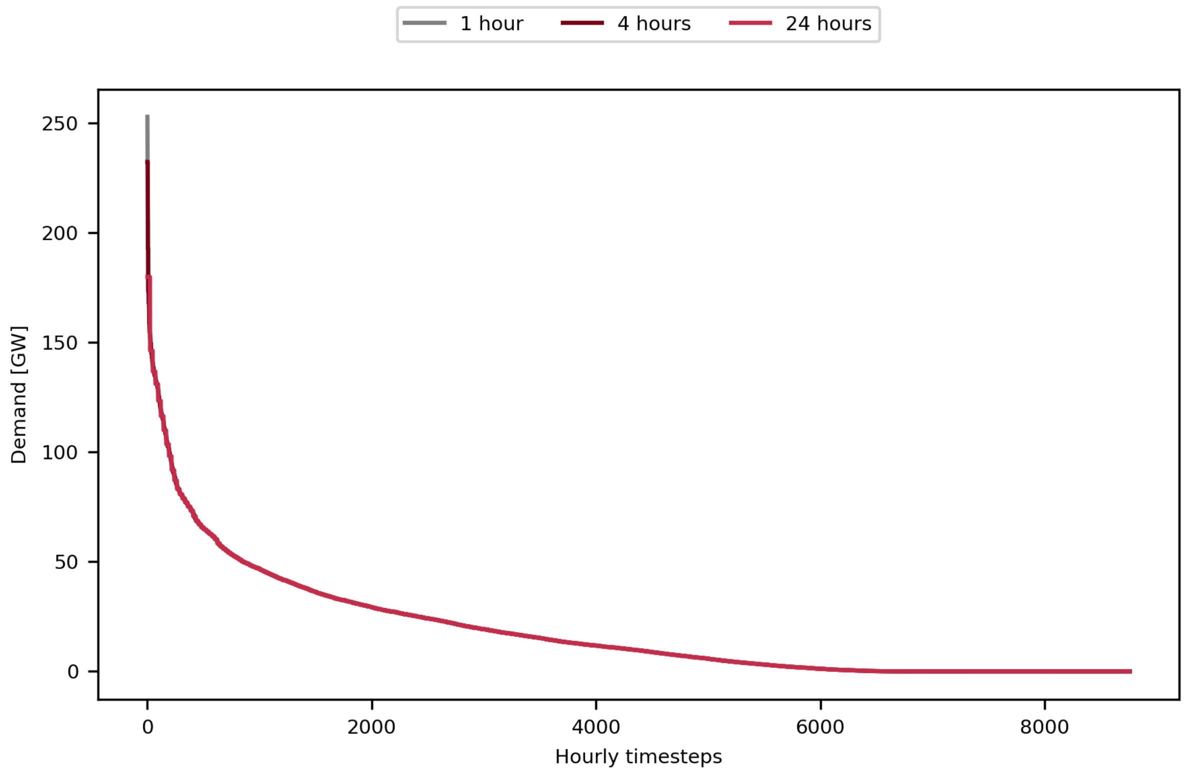


Figure 11: Load profile: Private and commercial heating demand for various resolution times, reference case (1 hour), 4 hours, 24 hours.

5.3.4. Entire heating sector

Previous sections considered different heat branches in detail. In Table 9, the assumptions for private, commercial and industry heat are aggregated to one Low Ambition and one High Ambition Scenario for the entire heating sector. The detailed heat branch scenarios will not be discussed in the results section, as this allows for a better comparability to the electricity and mobility sector.

Scenario	Residential/ commercial	Process heat low	Process heat mid	Process heat high
Low ambition	5.01%	8.6%	5.07%	3%
High ambition	34.21%	13.20%	12%	7.6%

Table 9: Demand reduction potential in Low and High Ambition scenarios for the heating sector.

6. Integrated Scenarios

So far all sectors have been considered individually. In this section, demand reductions due to sufficiency measures in all sectors are implemented at once.

6.1. Downward shifting load curve

As shown in Figure 12, two scenarios are identified, one for low ambition assumptions and one for high ambition assumptions, named respectively. Exact values are given in Table 10. The demand reductions are assumed to be the same for each time step, which lead to a downward shift of the demand load curve as shown in Figure 13a.

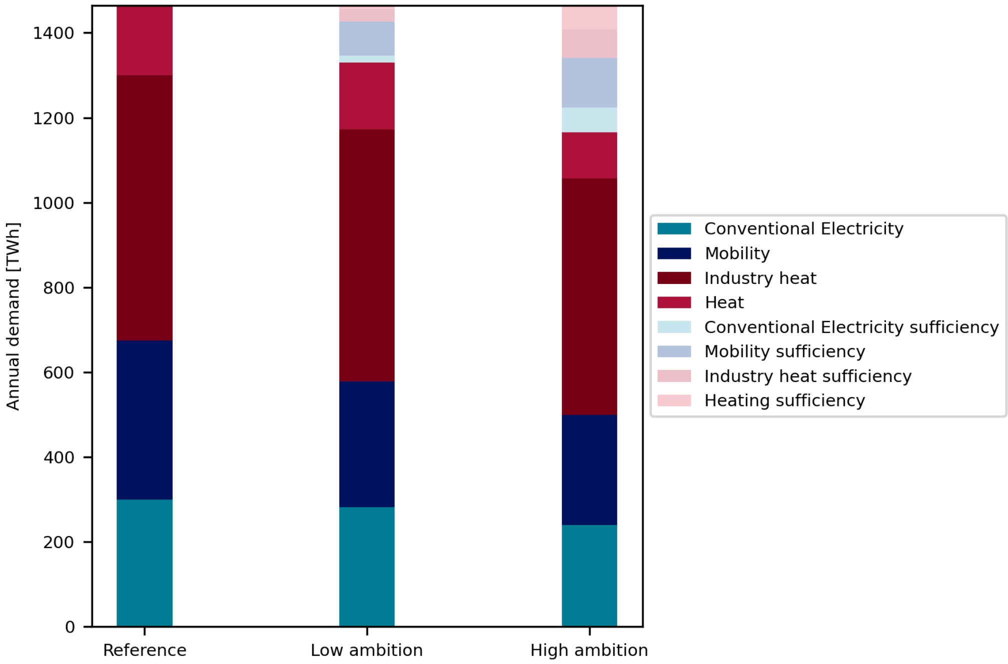


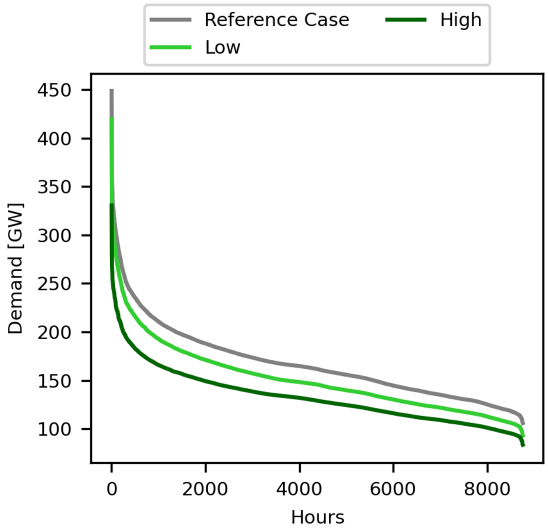
Figure 12: Visualization of scenario structure: Low and High ambitions of all three sectors.

	Reference	Low ambition	High ambition
Electricity sufficiency	0%	5.80%	19.90%
Mobility sufficiency	0%	21.70%	30.85%
Heating demand sufficiency	0%	5.01%	34.21%
Industry process heat sufficiency	0%	4.94%	10.94%

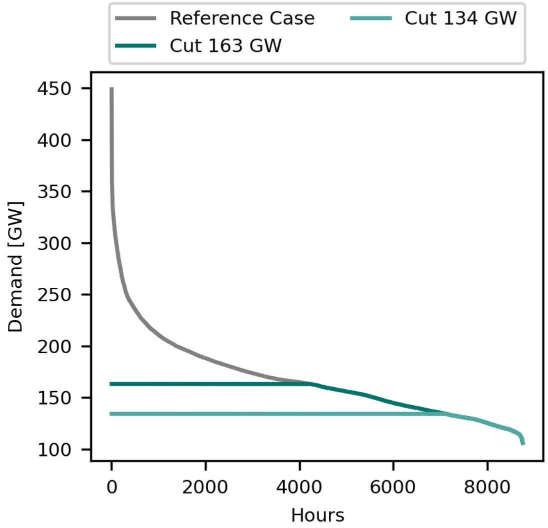
Table 10: Assumed demand reductions in each sector for the Low and High ambition scenario

6.2. Peak load shedding

The focus of this paper lies on the impact of sufficiency measures, which mean the downward shift of the demand curve as shown in Figure 13a for one Low and one High ambition scenario on consumer side. Additionally the impact of reducing only the demand in peak load hours is evaluated. Respectively Figure 13b shows the sorted demand curve with different reductions of the peak load hours. The peak load shedding demonstrates how strong demand peaks strain the energy system. The amount of reduced demand is the same for both methods.



(a) Demand load curve for sufficiency scenarios: Low and High ambition



(b) Demand load curve for peak load shedding scenarios

Figure 13: Comparison of demand curves for a) sufficiency scenarios (parallel downward shifting of the curve) and b) peak load shedding (cut curve for peak load hours).

6.3. Sensitivity scenario of peak load shedding

In the previous scenario explained in Section 6.2, the load peaks are reduced by the same amount of energy demand then the integrated Low and High ambition scenario in Section 6.1. To show what marginal effects the peak load shedding has on the total system costs, within this sensitivity analysis demand cuts from 300 GW to 150 GW are applied in 50 GW steps, together with the cuts at 163 GW and 134 GW. The respective load curve is shown in Figure 14, while the demand reduction is evenly distributed among all sectors.

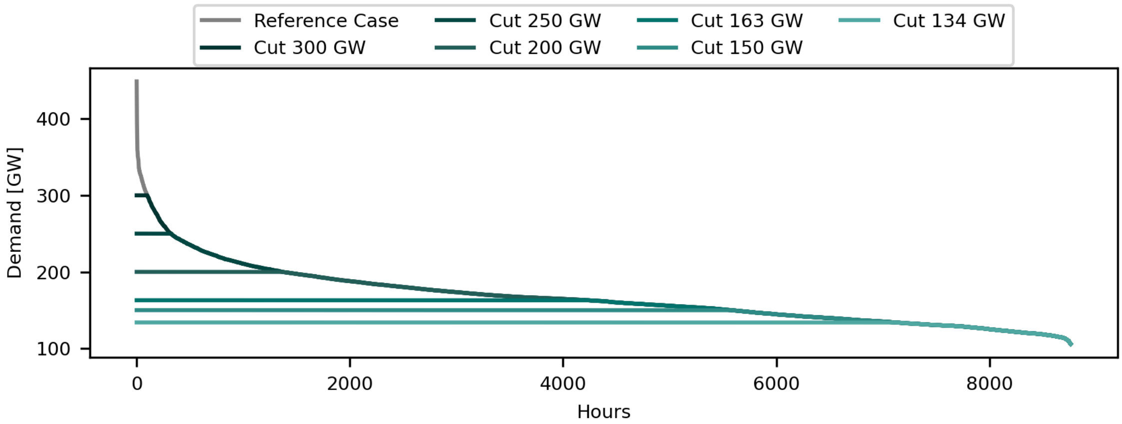


Figure 14: Demand profile for load shedding scenarios

7. Results

In this section, the impact of demand reduction scenarios in the previously described sectors on the overall energy system is presented. This includes the generation, storage and conversion capacities, as well as the associated system costs calculated by the linear cost-optimizing model.

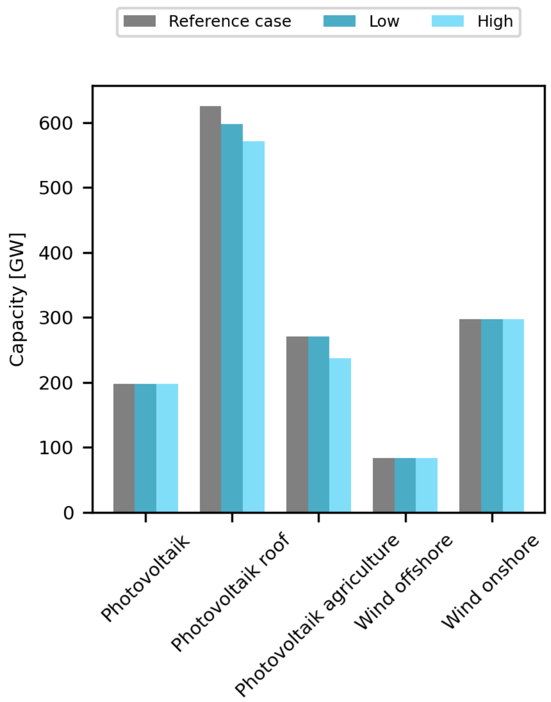
7.1. Conventional electricity sector

Following the reduction scheme presented in Section 5.1, the implications of reducing the conventional electricity load are presented in terms of capacity expansion and costs. Despite the diverse sector share, the absolute load reduction is distributed relatively evenly among both ambition scenarios. Table 11 lists the costs of the reference scenario and the sufficiency scenarios Low and High. The cost reductions in relation to the reference case are calculated, as well as the corresponding demand reduction through the different levels of sufficiency. In order to increase the comparability of the results, a relation between the achieved cost reductions and the prescribed demand reductions in the different scenarios is given. In a general view, the total systems costs were reduced in 1.35% and 4.61% for the Low and High sufficiency scenarios by reducing the total demand by 1.19% and 4.07%, respectively, reflecting the equally effect of both scenarios with respect to cost demand ratio index. However, achieving significant results entail the application of multiple reduction measures.

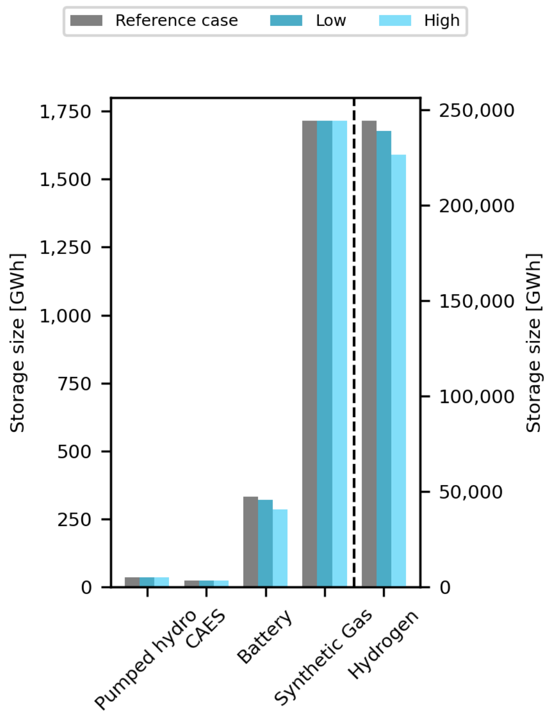
Scenario	Reference	Low	High
Total costs [M€]	119,399	117,781	113,888
Cost reduction	0%	1.35%	4.61%
Total demand reduction	0%	1.19%	4.07%
Cost/demand reduction ratio	0%	113.4%	113.3%

Table 11: Total system cost savings for the electricity sector

Reducing the electricity demand only brings a quantitative impact on roof and agriculture PV, while field PV expansion potential is used at its fullest since it carries lower investment costs. The Low Ambition Scenario causes only significant reductions on rooftop PV, while the High Ambition Scenario also leads to a decrease in agriculture applications. In contrast, both scenarios result in gradual reduction in most of the storage technologies. Figure 15 illustrates the optimal calculated values and relative changes in technologies' capacity for different scenarios.



(a) Capacity of renewable technologies



(b) Size of storage technologies

Figure 15: Visualization of installed renewable generation capacities (a) and storage size (b) for different demand reduction assumptions in the electricity sector

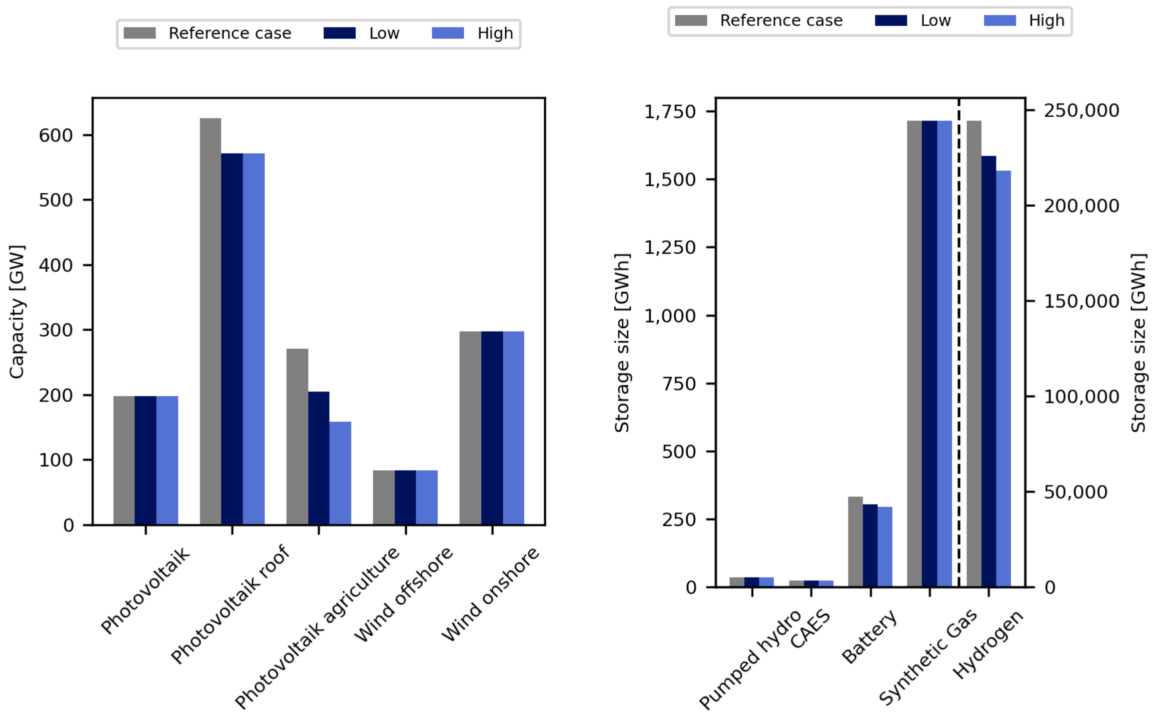
7.2. Mobility sector

Similar to the previous Section 7.1, Table 12 lists the results of the Low and High sufficiency scenarios in the mobility sector in addition to the reference case. It can be seen that a further demand reduction from Low Ambition Scenario to High Ambition Scenario in the mobility sector reduces the system costs proportionately.

Scenario	Reference	Low	High
Total costs [M€]	119,399	111,849	108,656
Cost reduction	0%	6.32%	9.00%
Total demand reduction	0%	5.56%	7.96%
Cost/demand reduction ratio	0%	113.7%	113.9%

Table 12: Total system cost savings for the mobility sector.

In the Low Ambition Scenario, the installed capacity is reduced by 7.21%. This was followed by a total reduction of 10.21% in the High Ambition Scenario. As already explained in the previous sector, a reduction in demand entails a lower expansion of PV systems on agricultural land followed by rooftop PV (Figure 16a). Furthermore, lithium-ion battery and hydrogen storage capacities are lowered.



(a) Capacity of renewable technologies

(b) Size of storage technologies

Figure 16: Visualization of installed renewable generation capacities (a) and storage size (b) for different demand reduction assumptions in the mobility sector

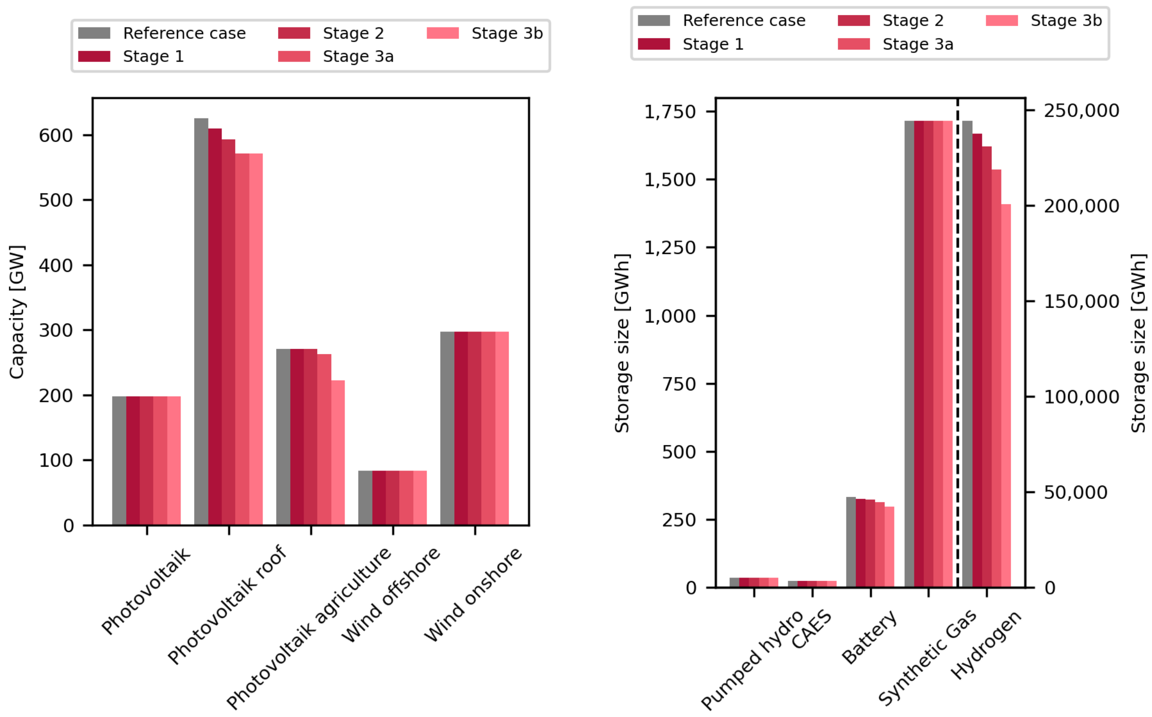
The Low Ambition Scenario has a total demand reduction of 5.56% (81.42 TWh). This leads to 24.4% less capacity installation of agricultural PV and 8.7% less of rooftop PV. Additionally, 9% (30.1 GWh) less li-ion battery storage and 7,5% (18.48 TWh) less hydrogen storage is needed. The significant reduction in hydrogen storage can be explained by its functionality. As hydrogen also serves as long term storage carrier, its reduction is not only driven by a direct reduction of hydrogen demand (air transport), but also from reducing overall electricity demand. Due to the fact that no exchange with other countries is allowed, neither for hydrogen nor electricity, reducing hydrogen production always leads to a reduction in electricity demand, reducing the necessary generation and battery capacity.

7.3. Heating sector

The following sections present the result from the reduction schemes presented in Section 5.3 excluding Section 5.3.4, which is evaluated in Section 7.4.2 together with the conventional electricity and mobility sector.

7.3.1. Reduction of private and commercial demand

In Section 5.3.1, different demand reduction stages are created to evaluate those impacts on the energy system. As can be seen in Figure 17, the installed PV capacity decreases. Additionally, less storage size is needed, which leads to total system cost reductions up to 6.29% (Stage 3b).



(a) Capacity of renewable technologies

(b) Size of storage technologies

Figure 17: Visualization of installed renewable generation capacities (a) and storage size (b) for different demand reduction assumptions in the private and commercial heating sector

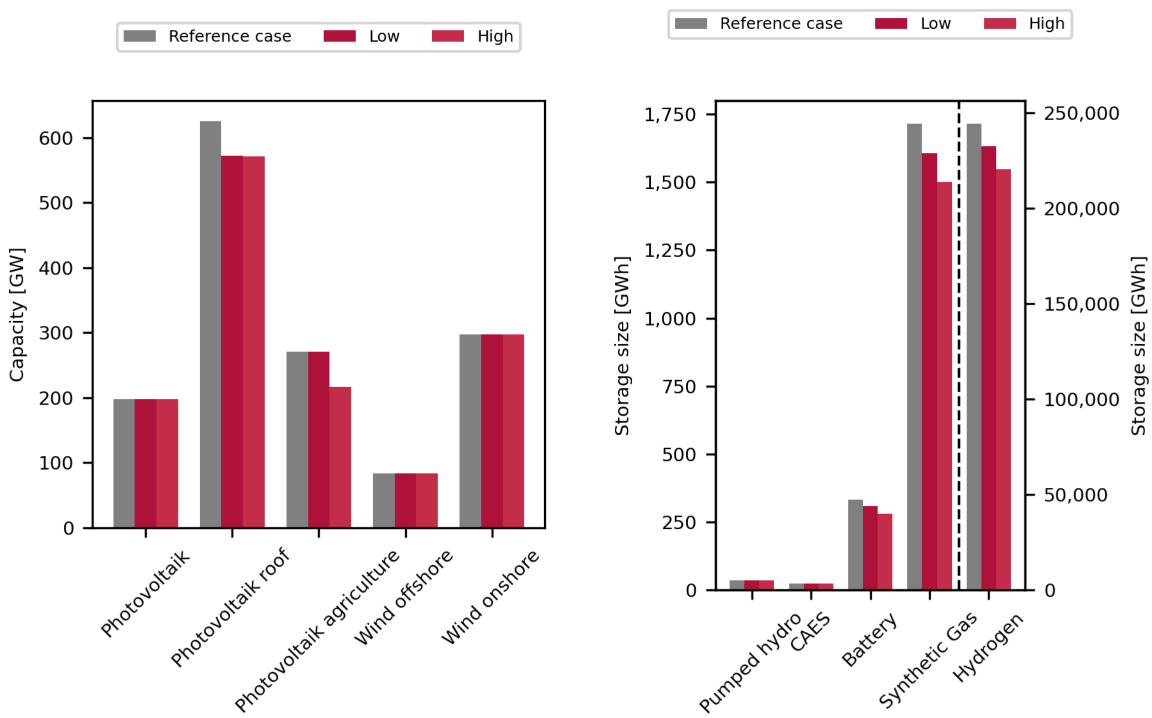
Although the cost savings appear to be negligible, they are disproportionately high when compared with the reduction in energy demand. For instance, in Stage 3b energy demand reductions of 3.86% is assumed, while system cost savings of 6.3% can be achieved. This supports the common perception that the last demand to be satiated is the most expensive, as additional energy storage is needed. In Table 13, the proportionality is calculated and varies between 170% and 163% achievable savings in relation to heating demand reductions. It shows that small reductions in the heating sector have a respectively high impact on the energy system costs. Compared to the electricity and mobility sector, the cost/demand reduction ratio is high for the private and commercial heating demand.

	Reference	Stage 1	Stage 2	Stage 3a	Stage 3b
Total costs [M€]	119,398	118263	117,161	115103	111,889
Cost reduction	0%	0,95%	1,87%	3,60%	6,29%
Total demand reduction	0%	0,56%	1,14%	2,19%	3,86%
Cost saving/demand reduction	0%	170%	164%	164%	163%

Table 13: Total system cost savings for the private and commercial part of the heat sector

7.3.2. Reduction of process heat demand

When evaluating the results of the proposed demand reductions concerning the industrial process heat, it is evident that the outcome is limited but reflects the linearity of the applied least-cost model. PV installed on roofs are reduced, as well as by PV installed on agricultural areas as their expansion investment cost is the highest. As all energy carriers are utilized for generating process heat, the respective storage capacities for batteries, synthetic gas and hydrogen are reduced from lowered demand. The effect is most visible for synthetic gas and hydrogen as seen in Figure 18. Comparing the overall system costs to the implemented demand reduction scenarios, up to 134% as a cost/demand reduction ratio is achieved in the High Ambition Scenario.



(a) Capacity of renewable technologies

(b) Size of storage technologies

Figure 18: Visualization of installed renewable generation capacities (a) and storage size (b) for different demand reduction assumptions in the industrial process heat sector

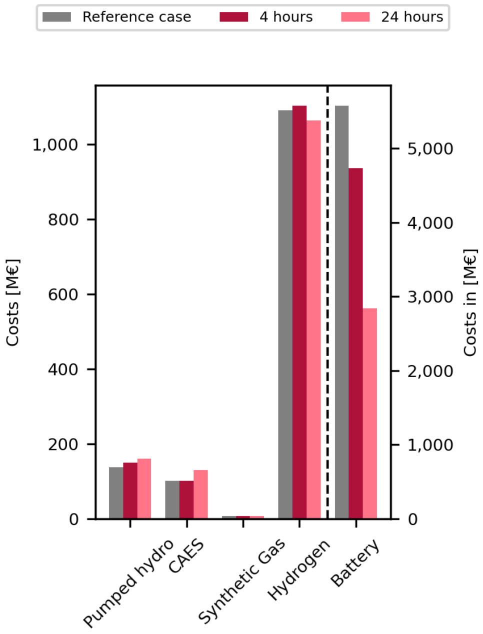
Scenario	Reference	Low	High
Total costs [M€]	119,399	116,135	112,229
Cost reduction	0%	2.73%	6.00%
Total demand reduction	0%	2.11%	4.48%
Cost/demand reduction ratio	0%	129.4%	134%

Table 14: Total system cost savings for the industry process heat sector

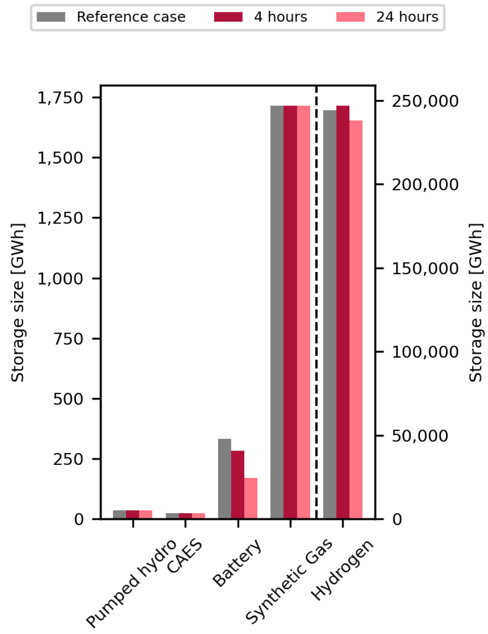
The exhibited result could be of greater scale if the interconnection between the industry branches would be considered when implementing sufficiency measures, as it is currently neglected due to simplifications. Additionally, every temperature level with its respective load curve could be investigated separately to showcase where the highest potential is situated within the industry branches. Because the high temperature demand curve is considered flat, all levels are considered collectively. Each industry branch is assigned one temperature level in order to simplify the underlying demand data. A more complex analysis here could lead to more accurate results, as this does not always represent real-world applications. As industry overlaps the other analyzed sectors, the implemented measures can be expected to influence quite significantly the industrial sector. These feed backs need to be examined holistically for every measure in further research. Additionally, there is the possibility to explore multiple sufficiency measures and their effect on the industry sector, as every behavioral lifestyle change implies a simultaneous change in the industry energy demand, partitioned in electricity and process heat demand.

7.3.3. Load shifting potential of heating demand

Results of the Load shifting scenario stated in Section 5.3.3 show that the required renewable capacities remain the same, while battery storage decreases greatly. With only a minor share of 11,28% of the total energy demand, the load shifting potential in the private and commercial heating sector reduces the amount of batteries needed by up to half (Figure 19b). Accordingly, the costs for batteries drop (Figure 19a). A reduction of the total system costs of 8-10% can be achieved without decreasing the total demand of energy but exclusively through the shifting of peak loads (Figure 20).



(a) Costs for storage expansion



(b) Size of storage technologies

Figure 19: Visualization of storage size and costs for different load shifting assumptions of the private and commercial heating demand sector

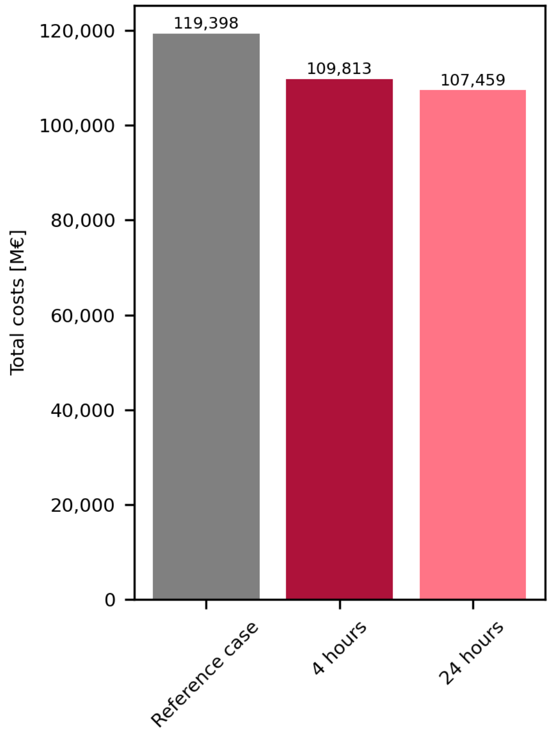


Figure 20: Total system costs with respect to different load shifting assumptions of the private and commercial heating demand.

7.4. Comparison of sectoral potential and impact

In contrast to the previous sector specific results, in this section all three sectoral demand reductions are considered simultaneously.

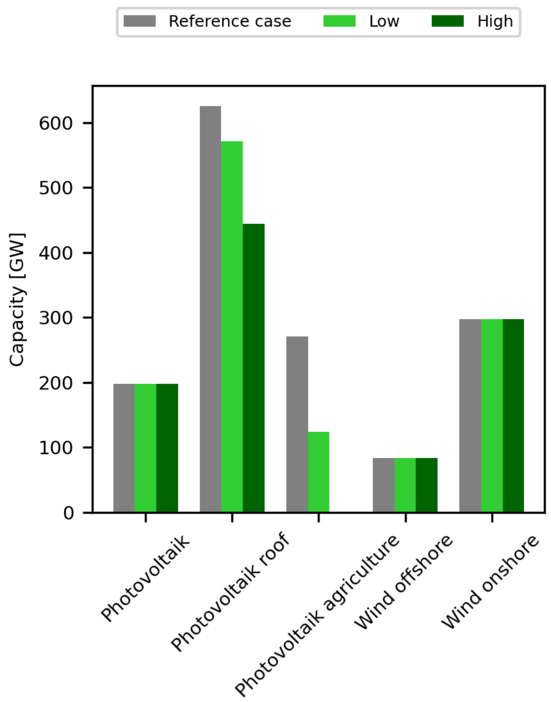
7.4.1. Integrated sector results

The scenario measures presented in Section 6.1 are discussed in the following section. The Low and High Ambition for the integrated scenario results in a system cost reduction of respectively 11.3% and 25.6%. The total system cost savings for the High and Low Scenario is listed in Table 15. From the table it can be seen that the cost saving per demand reduction is increasing. The proportionality increases by 4.6% from the Low to the High Ambition Scenario. Though counter-intuitive given the least-cost model employed, the High Ambition Scenario reduces a larger proportion of synthetic gas than the Low Ambition Scenario, resulting in larger cost savings given the loss in inefficiencies from electrolysis and methanation versus direct use of electricity.

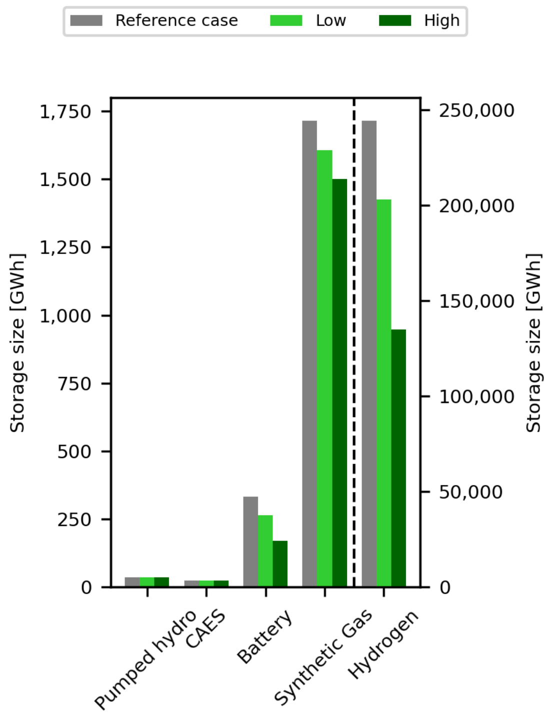
Scenario	Reference	Low	High
Total costs [M€]	119,399	105,897	88,867
Cost reduction	0%	11.3%	25.6%
Total demand reduction	0%	9.4%	20.5%
Cost/demand reduction ratio	0%	120.2%	124.8%

Table 15: Total system cost savings combined sector Low and High scenario

The demand reduction in the Low and High Ambition Scenarios lead to an overall renewable capacity reduction of 13.61% and 30.63% respectively, as well as a storage size reduction of 16.8% and 44.5%, respectively. The need for capacity and storage is decreasing with regards to the demand reduction. The largest storage reduction comes from hydrogen storage, as can bee seen in Figure 21, because the need for long term storage is decreasing. Figure 21 shows what the previous sections have concluded, i.e. the PV capacity is reduced. In the High ambition scenario the overall PV is reduced by 41.3%, and the need for agricultural PV goes from 270.45 GW to 0 GW.



(a) Capacity of renewable technologies



(b) Size of storage technologies

Figure 21: Visualization of installed renewable generation capacities (a) and storage size (b) for Low and High ambitions scenarios

7.4.2. Comparison of sectoral results

Figure 22 compares the sector-specific High Ambition Scenario effects on generation capacities, storage sizes and total system costs. In each scenario only one sector's demand is reduced, while the other two remain unchanged. The heat and mobility sector each have a demand reduction potential of about 8% of the total energy demand, visible in the left subplot of Figure 22. It is noticeable, that these similar reductions lead to storage reduction of approximately 11% for the mobility sector and 27% for the heating sector. Therefore, substantial cost savings for storage technologies are attainable, with li-ion batteries alone showing a potential savings of 1,500 M€ (Figure 23b).

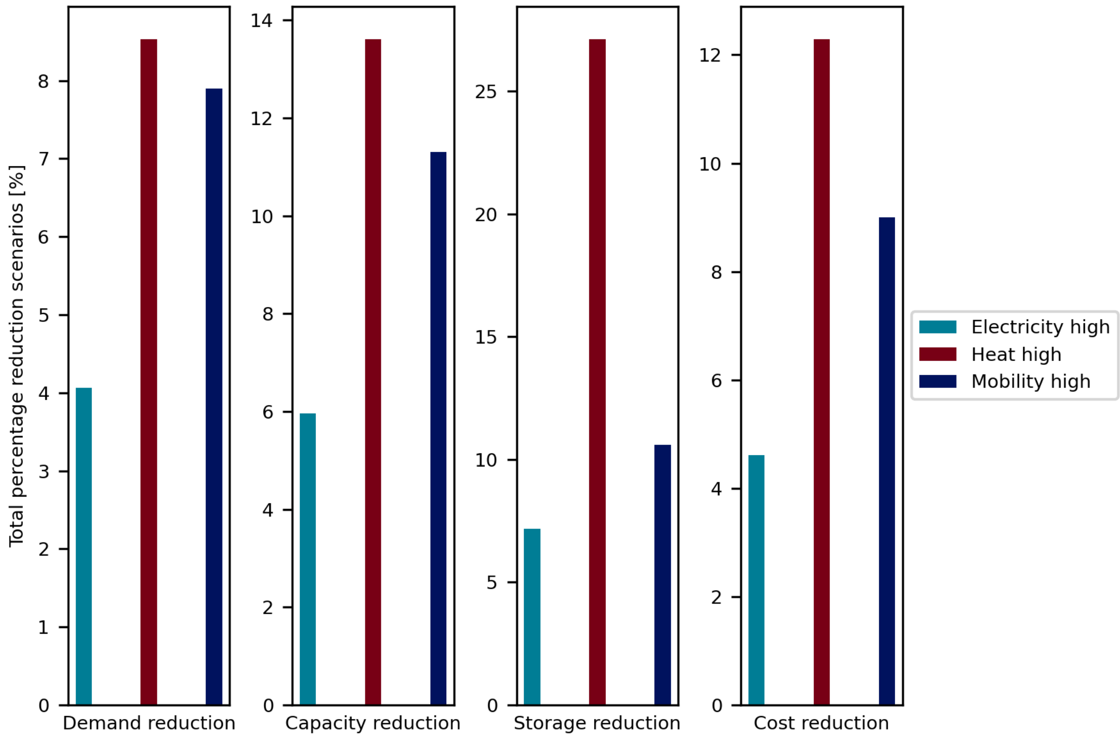
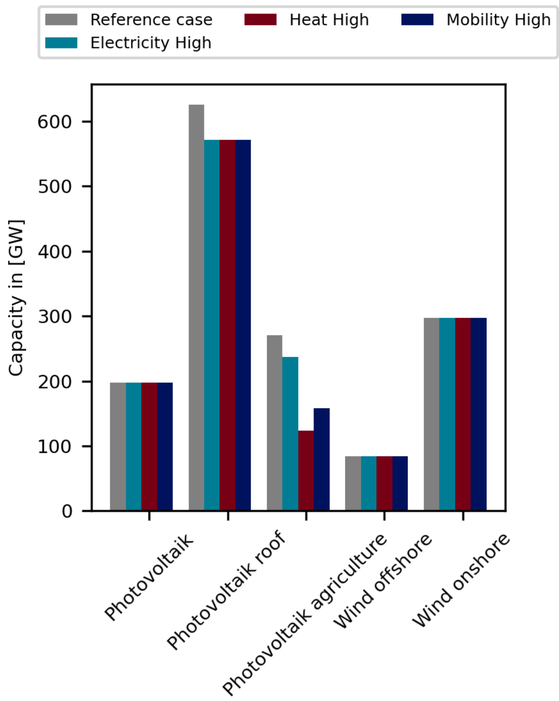
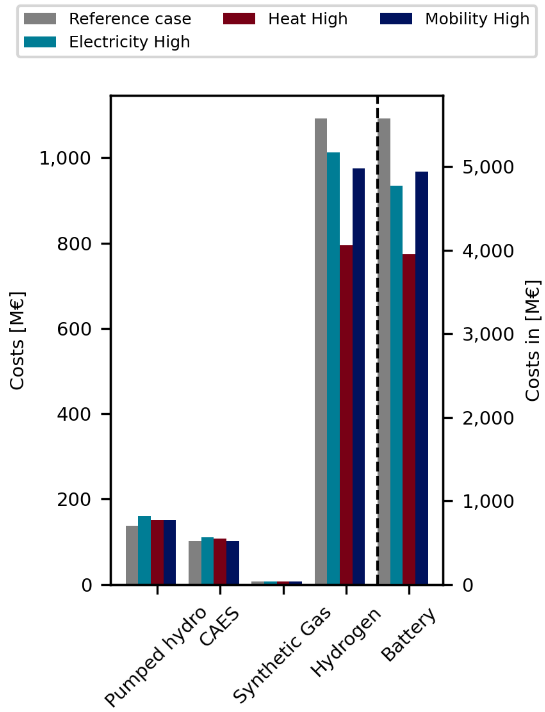


Figure 22: Comparison of the High ambitions scenarios impact to the energy system for the three sectors.

Along with large storage size and cost savings, caused by prominent peaks in the residential heating demand, a renewable capacity reduction of 13.5% is achievable if the sufficiency potential of the heat sector is fully exploited. Figure 23a shows that the heating sector has the highest potential of reducing the required PV expansion, and therefore decreases the associated land use. When the heating sector is observed exclusively, a total system cost reduction of 12.3% is attainable, followed by the mobility sector with a total system cost reduction potential of 9% and the electricity sector with 4.6% savings. Hence, the heating sector has the largest impact on the energy system's supply side.



(a) Capacity of renewable technologies



(b) Cost of storage technologies

Figure 23: Visualization of installed renewable generation capacities (a) and storage cost (b) for High ambitions scenarios of all sectors and reference case

7.4.3. Peak load shedding results

Two methods to implement demand reductions are explained in Section 6.2 and evaluated in the following. As shown in Figure 24, the percentage demand reductions of a combined Low ambition scenario equal a peak hour shedding at 163 GW, analogously the combined High ambition scenario and the peak hours cut at 134 GW equal in amount of demand reduction. As explained previously, peak loads require large amounts of storage size to meet demand. Storage reduction for the combined Low scenario reach a level of 16%, while the same demand reduction in the peak load hours only, reach a storage saving of 45%. Furthermore, savings in renewable capacity expansion are visible, even though they are respectively small compared to additional storage size savings. The renewable capacity savings for the combined Low scenario is 13% while that of the peak hour shedding at 134 GW is almost 3% more.

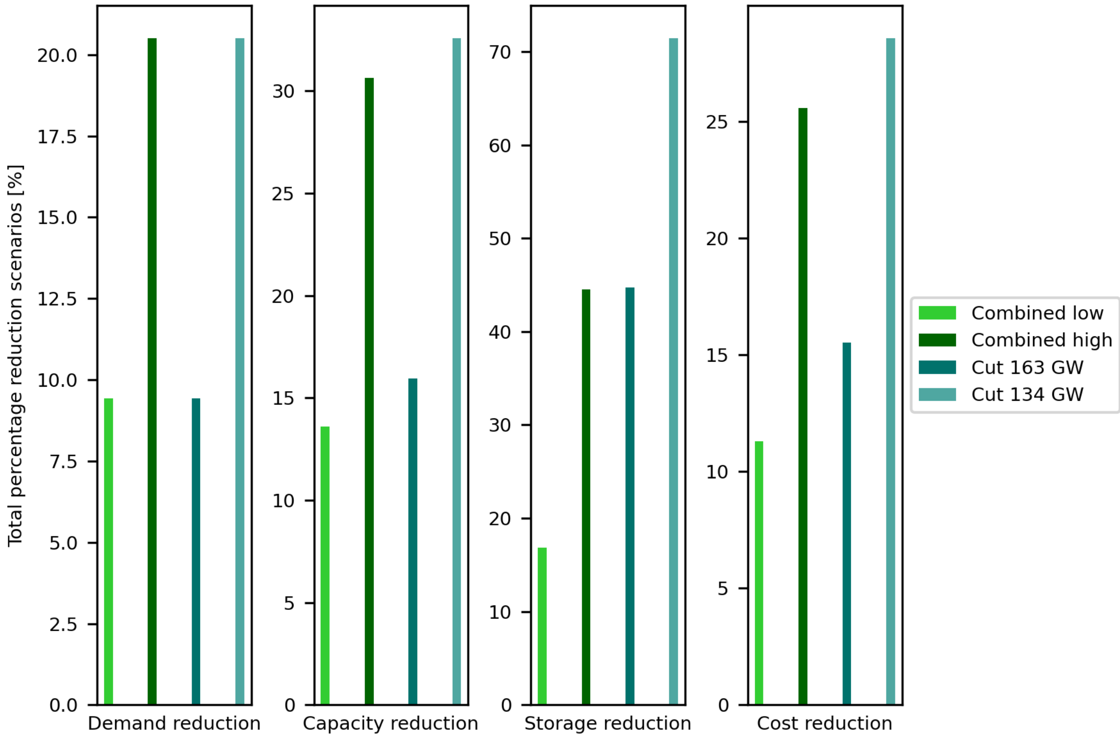


Figure 24: Comparison sufficiency scenarios and peak load shedding to include the same amount of demand reduction.

Differences between total system cost savings of the two reduction methods are within the expected and vary between 4.2% and 3% (Table 16). Hence, additionally savings of 4.2% are reachable, when peak shedding is applied, instead of an equal demand reductions in each time step. It must be assessed whether the cost savings are respectively large enough to compensate for the effort required, when enforcing a peak load hour shedding.

	Reference	Combined Low	Cut at 163 GW	Combined High	Cut at 134 GW
Demand reduction	0%	9.3%	9.3%	20.8%	20.8%
Total system costs [M€]	119,398	105,897	100,869	88,867	85,299
Total cost reduction	0%	11.3%	15.5%	25.6%	28.6%

Table 16: Comparison of total system cost reductions for two different methods of implementing demand side reductions.

7.4.4. Sensitivity analysis of peak load shedding

In the following, the peak load shedding explained in Section 6.3 is evaluated. Figure 25 shows the decrease in installed technologies and the corresponding costs with decreasing peak loads from left to right. As expected, reductions in capacity, storage, and cost increase along with demand. Nevertheless, it can be seen that the top cuts have the greatest proportional influence. The cut at 250 GW, only reduces demand by 0.84%, but there is a corresponding decrease of approximately 2% in Renewable Energy Sources (RES) capacity and 5% for storage. This is a multiple of the energy demand reduction corresponding to a decrease of more than twice, and six times the reduction in energy demand, respectively. Looking at the next cut at 200 GW, this corresponds to a demand reduction of a further 2.47% to a total of 3.31%. Here, too, there is a decrease in the required expansion of generation capacity by twice the decrease in demand, and in storage capacity by about five times. A look at the costs reveals, nevertheless, that the cut at 250 GW saves almost three times as much in costs, while the cut at 200 GW only saves twice as much as the demand reduction. This is intuitive, given the lead-cost nature of the model used.

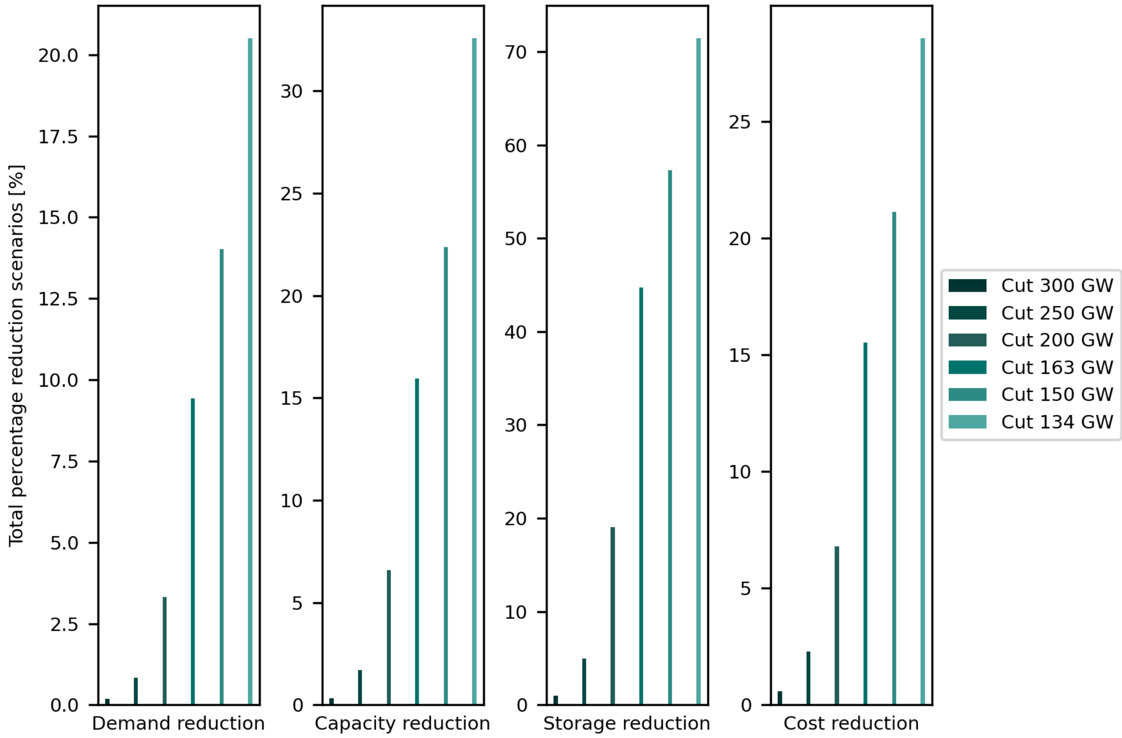


Figure 25: Total reductions of load shedding scenarios

8. Conclusion

Technological development and political commitments are beginning to enable the vision of a sustainable, carbon-neutral society. Worldwide investment is rising in renewable energy research and development, and installed capacities of wind and solar continue to grow. However, political and public acceptance can shift, as technology will inevitably be constrained by the physical space allowed for renewable capacity expansion. The ongoing discussions on pathways towards net-zero economies have centered their focus on adapting the industrial apparatus to sustain its consumption trends. Now, every possible solution must be explored thoroughly to ensure the most efficient pathway towards a sustainable future.

This paper investigates a relatively unexplored topic within energy planning: the value of reducing the absolute energy demand through behavioural changes. Modifying human behavior becomes a complex task when individual needs are tackled. Consequently, many contributions to this field have not attracted much attention to the public and hence to political agendas. For alternative solutions to be taken seriously, studies focused on demand reduction must introduce feasible changes to consumption behaviors, while producing competitive results. Such studies do not include efficiency or other technological solutions, but are instead are focused on people's actions, individual and collective. Through extensive literature review, reasonable demand reductions were arrived at based off personal choices, whether it be cycling more often to work, telecommuting, reducing consumer purchasing, or reducing the temperature in one's household.

A least-cost energy system model is applied to model the effects of behavioural changes on the supply side. The model minimizes total system costs of a greenfield, 100% renewable energy system for Germany, using costs assumptions for 2035. Results show that a reduction of up to 20% of the required generation and storage capacity is achievable. A such reduction would also decrease the amount of land needed to support the installation of renewable generation technologies, such as in case of wind and solar. This can potentially reduce political friction, increasing social acceptance of further renewable capacity expansion and create incentives for further reductions in demand. Additionally, savings in marginal and investment cost can reach up to 25%, reducing not only the amount of resources needed but also increasing the feasibility of the model within the considered time frame.

The scarcity of research on demand reduction and similar topics makes this field of investigation relatively open to further expansion. Models targeting change in social behavior can be tested against typical opposing arguments such as rebound or spillovers effects (Sorrell et al., 2020). The presented framework for this paper can also be extended by testing it in more complex designs by adding neighbours countries and their respective energy exchange. It has been shown that these sufficiency measures are feasible and have a significant impact on the German energy system. Therefore, sufficiency must be considered as a policy option to reducing energy demand in Germany and hence support the transformation of the energy system.

A. Supplementary data

Technology	Cost (€/kW)
Offshore Wind	3111.24
Onshore Wind	1199.22
Rooftop PV	594.20
Open-space PV	406.97
Agricultural PV	813.94
Electrolyzer	542.49
Methanation	865.32
Hydrogen Plant	184.90

Table A.1: Technology cost assumptions, 2035 (Kost et al., 2018; Trommsdorff, 2020; Göke et al., 2019).

Category	Sub-Category	Measures	Energy demand [TWh]	Low Ambition Reduction [%]	Low Ambition Reduction[TWh]	High Ambition Reduction [%]	High Ambition Reduction [TWh]
Air	Passenger	a) Telemeetings b) Shift to train c) Reduction of private flights	10.35	62%	6.4	80%	8.3
	Freight	a) Shift to train b) Shift to ships	255.54	20%	51.1	30%	76.7
Road	Passenger	a) Increase in bicycles b) 1 day of home office c) Efficient driving d) Telemeetings e) Smaller private vehicles	55.06	14%	7.7	14%	7.7
	Freight	a) Fuel Optimization b) Driver Management c) Space Optimization d) Less online shopping returns	17.73	29%	5.1	44%	7.8
Rail	Passenger	a) Increase in bicycles b) 1 day of home office c) Telemeetings	12.74	38%	4.8	38%	4.8
	Freight	a) Time Table Optimization b) Driving Optimization	23.84	26%	6.2	44%	10.5

Table A.2: Detailed demand reduction potential in Low and High Ambition scenarios for air, road and rail mobility demand.

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