

Article

Modeling of Persistence, Non-Acceptance and Sufficiency in Long-Term Energy Scenarios for Germany

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Abstract: Long-term transition pathways to a low-carbon energy system are analysed by applying the energy system model REMod. All in all, the paper contributes to the current research through an innovative scenario approach, using assumptions for societal trends and quantitative results for scenarios, analysing the paths towards climate neutrality and defossilization in 2050. In the case study of Germany, these trends and drivers influence the results and the technology composition in each consumption sector (buildings, transport, and industry). Across all scenarios, it can be observed that the electrification of all sectors is important for the defossilization of the energy system, as the direct use of electricity from renewable energy is more efficient than the consumption of carbon-neutral synthetic energy carriers. However, different consumer behavior (e.g., non-acceptance or resistance against specific technologies) influences not only the efficient use of (green) electricity, it also changes the optimal pathways of the transition to paths with greater efforts. One potential societal trend—sufficiency—could be an important cornerstone for reaching the targets, as the required expansion and exchange of technologies are lower and thus facilitate the transition.

Keywords: transition pathways; energy system modeling; societal trends



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1. Introduction

In June 2020, Germany published its National Energy and Climate Plan (NECP). The plan contains the roadmap to reach the CO₂ emission reduction measures and targets for the country's energy system and its electricity, heat, industry, and transport sectors [1]. The Climate Action Plan 2050 clearly states that Germany supports the Paris COP21 agreements and aims to achieve climate neutrality by 2050 [2]. However, both plans leave open how each sector will contribute in the long-term achievement of this goal by 2050. Climate neutrality means for Germany to reach zero or nearly-zero CO₂ emissions in the energy system [2].

Currently, the German energy transition (“Energiewende”) is facing various challenges in pursuing the long-term transformation paths towards zero CO₂ emissions by 2050. In the heat and transport sectors, the exchange rates of end-user applications necessary for the transition of the energy system are very low. For example, in the field of electric vehicles or heat pumps, the numbers of new installations and purchases lag behind those of other countries [3]. Deployments and new installations of onshore wind power plants have decreased to below 1 GW_{el} per year in 2019, as local acceptance, land use, and construction permits are more difficult to obtain [4]. In the fields of energy efficiency and consumption reduction, all sectors (heat, industry, and transport) show stable or increasing demand (e.g., due to an increase in comfort or travel needs). On the other hand, however, new innovative technologies and behavioral patterns have provided a new boost to the energy transition. The increasing use of PV battery systems, the national hydrogen strategy, and

the “Friday’s for Future” movement have provided new opportunities and perspectives in the transformation process [5,6]. The coronavirus crisis has prompted interesting changes in areas such as “working from home” or “local holidays”, which need to be tested to see if they will continue after the crisis and change the energy consumption in the long-term.

The key research question of this paper is how the energy transition can be accomplished by considering and reflecting on recent societal trends in the transition pathways. The present paper provides new insights by linking the recent climate policy targets of an emission reduction of at least 95% by 2050 with recent societal trends in a large energy system model. The following trends were selected, as they appear to have the highest appearance in current societal and political discussion: persistence, non-acceptance, and sufficiency. Persistence can be explained as a social and market-economy trend that involves not exchanging certain technologies, but rather transforming their application with the use of low-carbon technologies, as their use is well known, and owners and users of this technology have extensive previous experience. Non-acceptance is an important trend in many societies nowadays, where resistance to and the lack of acceptance for new technologies (e.g., the not-in-my-backyard (NIMBY) phenomenon) are widely known. Sufficiency is also a new trend in energy use as individuals show an awareness to reduce their own resource- and energy-intensive behavior within the ambition to face climate change. An analytical model approach that maps the climate policy objectives of the German government in a sector-coupled energy system model, considering both hourly operation and annual expansion, while at the same time applying storylines that show societal trends such as persistence with specific technologies, non-acceptance of structural changes and sufficiency, has not yet been developed.

This paper is based on the study “*Paths to a Climate-Neutral Energy System—The German Energy Transformation in its Social Context*”, which was published in February 2020 [7]. However, here, the analysis is extended to explore the structure and energy flows of each sector. To address the aspect of uncertainty in the results, additional scenarios are examined for a sensitivity analysis relating to two key technological aspects. As mentioned above, the number of installations of battery systems is currently increasing in Germany [6]. At the same time, battery costs have fallen drastically in recent years. Another technology with dynamic development is the use of hydrogen, for which Germany has declared a national hydrogen strategy. Furthermore, import routes and supply chains have been discussed [5]. For both technologies—battery storage and hydrogen as an energy carrier—sensitivity analysis on the cost developments over the years up to 2050 are added to the main scenarios.

The outline of the paper is as follows. First, a literature review is provided. Then the model methodology is described, including the construction of scenarios that include technological and societal trends and the key input parameters of the sensitivity analysis for battery storage and synthetic fuels. Then the scenario results are presented, which are split into general results for the transformation paths and specific results pertaining to the sensitivity analyses. We discuss the results and draw conclusions.

2. Literature Background

To analyse long-term developments and uncertainties in the energy sector, energy system models help to create scenarios and depict systemic relationships. They can thus form a basis for political decisions in the field of energy transition, especially in fields where strategies currently are not yet defined. [8] identifies four challenges for energy system models: resolving time and space, uncertainty and transparency, growing complexity and integrating human behavior. [8] states: “*However, much of what stands in the way of technology deployment is political will, public acceptance, behavior and the difficulty of changing it. This leads to a final shortcoming, a tendency to focus on factors that lend themselves to modeling (i.e., technological and economic factors), but a relative neglect of factors that may be equally or even more important, such as human behavior, indirect costs, or socio-political and non-financial*

barriers to deploying technologies.” [9] highlights that the field of social science is greatly underrepresented in energy system modeling.

In the field of energy system analysis, societal factors have been addressed in modeling for the German energy system, with a focus on wind power in [10], and on the electricity grid in [11], in which the *renpassG!S* model was applied. [12] integrated aspects of the acceptance and the participation of renewable energy sources into the *ENERTILE* model.

The “story and simulation (SAS)” approach includes societal factors and qualitative information in scenario modeling [13]. Using this approach, qualitative storylines are developed, and the driving forces of the storylines are translated into numerical data, serving as an input for the model. This approach has been criticized, as SAS approaches show little reproducibility, as they are mostly deduced in expert workshops, and the translation from qualitative to quantitative data requires interpretation [14]. Another approach is to use cross-impact balance (CIB) analysis for the storyline construction process [15] to enhance consistency [16]. In [17], the CIB approach was applied, using the *ENTIGRIS* model to analyse the effect of regional self-supply targets in Germany on the electricity system.

An overview of existing systematic studies for the long-term transformation path of the German energy system can be found in [18]. Specifically, four recent publications and studies of the policy process in Germany [19–22] provide a technology and emission-target-based analysis for all scenarios. Nonetheless, none of these studies combine a specific societal context with their scenario approach.

3. Methodology

In the following section, the *REMod* energy system model is first described briefly with regard to its objectives and methodology (Section 3.1). Then, the scenarios are described, along with their narrative and basic assumptions, which are quantified in Section 3.2. In order to address the aspect of model uncertainty, the assumptions of the sensitivity analysis regarding battery costs and power-to-X are explained in Section 3.3.

3.1. Scenario-Based Analysis with *REMod*

The methodology of this paper is based on the study “*Paths to a Climate-Neutral Energy System*” [7]. The objective of the scenario analysis is to describe and evaluate possible and consistent future developments based on the currently available knowledge on the energy system of Germany. The main aim of modeling with *REMod* is to analyse, from a system engineering perspective, the development of an energy system that is constrained by a fixed emission budget and to determine the overall system cost. The basic idea of the model is to identify technically and economically feasible transformation paths for the German energy system. At the same time, these paths should comply with the defined climate policy goals for reducing energy-related CO₂ emissions. A central feature of *REMod* is the simultaneous optimization of all consumption sectors of the energy system, with a high temporal resolution [23,24]. The simulation considers a consistent timeline from today up to 2050 with an hourly resolution. By simultaneously optimizing all sectors of the energy system (electricity, building heating, industrial process heat, and transport), the mutual influence of these sectors is considered. All relevant energy sources, converters, and storage facilities and all consumption sectors are mapped in the model.

The geographical focus on Germany was chosen as the German energy system is facing a long-term energy transformation to a climate-neutral system within the next 30 years. Additionally, the *REMod* model applied in this paper is well established in energy-system modeling research, with a well specified and validated data set for Germany through various studies conducted in recent years [18,25,26].

More details on the modeling approach can be found in [23–25], as well as in the correspondent study [27]. More details on the data input can also be found in the study.

3.2. Construction of Scenarios Including Technological, Societal, and Political Trends

The transformation of the energy system is not only a question of technical and economic development. Societal interest drives the transformation, since ultimately investment and demand behavior, as well as the use of technologies, depend on individual and professional actors and their behavior. For this reason, various scenarios are presented in this framework to illustrate a possible range of behavioral patterns. The basic assumption of the scenarios is a 95% CO₂ reduction compared to 1990. In order to limit the temperature increase to well below 2 °C, as agreed upon in the Paris Climate Convention, the German climate protection program aims to achieve a climate-neutral energy supply [28].

Four storylines were examined during expert workshops. The main assumptions are summarized in Table 1, and further details can be found in [27]. There is a *reference scenario* that serves as a comparison scenario, which is characterized by moderate developments and limitations in the transport, building, and industrial sectors.

The *persistence scenario* is characterized by the assumption that individuals in their immediate surroundings have only a low acceptance of new technologies and that investment decisions are made to a large extent in favor of conventional technologies. High market shares of alternative vehicles (around 88%) can only be achieved through extreme efforts, as Senkpiel et al. show, taking into account consumer preferences and using a stock model. In a scenario with conservative assumptions, only a 38% market share of alternative vehicles was simulated for 2050. Therefore, the assumption for the *persistence scenario* is that at least 50% of newly registered cars are based on conventional combustion engines and that individuals are not willing to supply flexibility to the grid with the batteries of electric vehicles. Similar assumptions apply to the heating system and building retrofit: “Another study regarding heating systems, using a different choice heuristic (like imitation or recognition), lead to a comparable investment tendency, leading to a high share of the well-known/trusted technology of gas boilers.” [29]. The Invert-EELab model simulates the adoption of heating systems based on discrete choice experiment data and the derived utilities for the alternative heating systems. According to the bottom-up Invert simulation presented in the reference scenarios of [30] or [31], gas boilers have the highest market share in 2050. Therefore, a minimum installation rate of 50% for gas-boilers and a renovation rate of 1% is assumed in the *persistence scenario*.

The basic assumption in the *non-acceptance scenario* is that major infrastructural changes, such as electricity grid expansion, wind farms or overhead power lines for busses and trucks, will enjoy little local acceptance and face protests [12]. Therefore, the expansion potential is reduced (see Table 1). In [10], the authors calculated the socio-ecological expansion potential of wind onshore plants on the basis of a load level, considering the usable wind area in relation to the district area and the population density. The presented trend scenario considers current trends, as well as qualitative storylines regarding the future participation commitment of the local population. The Wingman scenario resulted in a wind power expansion of about 76.7 GW. Therefore, the wind onshore expansion is limited to 80 GW in the *non-acceptance scenario*. The current export interconnection capacity in relation to Germany’s neighboring countries is around 21.5 GW. Although in the *reference scenario* an increase to 40 GW is assumed, based on [32], in the *non-acceptance scenario* the assumption is made that the expansion of the interconnectors is limited to 20 GW, assuming public opposition (such as the NIMBY effect) [33], leading to significant delays for new transmission lines. The delays can be up to 10 years, based on the investigations of [11]. In addition, no overhead lines for trucks and busses are constructed, as the acceptance is missing on a local level.

In the *sufficiency scenario*, individuals show an awareness of climate change that leads to less resource- and energy-intensive behavior. According to [34], there are three pillars for achieving climate protection goals and the reduction of CO₂ emissions: efficiency, consistency, and sufficiency. The efficiency strategy aims to improve the ratio of input to output, i.e., the efficiency of the system. The expansion of renewable energies and a reduction of emissions through technical solutions can be included under the category

of consistency [35]. The pillar of sufficiency addresses the reduction of demand (of GDP) based on the change in individual behavior. Current climate policy primarily addresses the measures of the efficiency and consistency pillar [36]. [34] presents several reasons why efficiency and consistency are not sufficient to achieve the climate protection goals. The limits of efficiency are the rebound effect, economic growth, and opposing trends. The limits of consistency are the uncertainty of technology and global justice. [36] illustrates that there is a great need to consider sufficiency in energy scenarios. However, there is not yet a sufficient database for the analysis of the potential sufficiency scenario. Therefore, the *sufficiency scenario* assumes that the basic electricity load will decrease by 45% by 2050, 30% fewer passenger kilometers will be covered by car, domestic air traffic will be reduced by 55%, and the demand for industrial process heating will decrease by 0.75% per year. At the same time, efficiency is addressed in the building sector, so that homeowners are increasingly refurbishing (2–3% refurbishment rate). This finally leads to the scenarios presented in overview in Table 1.

Table 1. Scenario assumptions. Unless otherwise stated, this means that the assumptions of the reference scenario apply.

	Reference		Persistence		Non-Acceptance		Sufficiency	
Potential PV (GW)	-	530	-	530	-	800	-	530
Potential Wind Onshore (GW)	-	230	-	230	-	80	-	230
Potential Wind Offshore (GW)	-	80	-	80	-	40	-	80
Interconnector capacity (GW)	-	17 in 2020 40 in 2050	-	17 in 2020 40 in 2050	-	17 in 2020 20 in 2050	-	17 in 2020 40 in 2050
Electricity demand for lightning, cooling, ICT, mechanical energy	-	Yearly demand is constant (400 TWh), compared to today	-	Yearly demand is constant (400 TWh), compared to today	-	Yearly demand is constant (400 TWh), compared to today	-	Yearly demand decreases by −45% in 2050 (−180 TWh) compared to today
Import synfuels	-	Available from 2030 onwards, price path was calculated	-	Available from 2030 onwards, price path was calculated	-	Available from 2030 onwards, price path was calculated	-	Available from 2030 onwards, price path was calculated
Road traffic capacity	-	Growth of 3.5% for passenger cars (2020 400 TWh)	-	Growth of 3.5% for passenger cars (2020 400 TWh), and of 27% freight (2020 185 TWh), by 2050	-	Growth of 3.5% for passenger cars (2020 400 TWh), and of 27% freight (2020 185 TWh), by 2050	-	Reduction by 30% in passenger car capacity
	-	27% growth for freight (2020 185 TWh), by 2050	-	27% freight (2020 185 TWh), by 2050	-	27% freight (2020 185 TWh), by 2050	-	freight constant
	-	air traffic constant (100 TWh)	-	air traffic constant (100 TWh)	-	air traffic constant (100 TWh)	-	55% air traffic reduction
Transport	-	Overhead contact lines (freight)	-	Min 50% vehicles with conventional combustion engine (passenger cars)	-	No overhead contact lines (freight)	-	8% of battery capacity can be used for V2G and G2V
	-	max. 80% new BEV registrations	-	No V2G/G2V	-	small share of BEV for freight	-	
	-	10% of battery capacity can be used for vehicle-to-grid and grid-to-vehicle	-		-		-	
Buildings	-	8% increase of heated building area until 2050	-	min 50% gas boilers of new installations	-	8% increase of heated building area until 2050	-	minimal renovation rate increases from 1% to 2% by 2050
	-	heat pumps max 85% of new installations	-	Renovation rate constant (1%)	-	heat pumps max 85% of new installations	-	
	-	max. renovation rate increases from 1% to 3% by 2050	-		-	max. renovation rate increases from 1% to 3% by 2050	-	
Process heating (industry)	-	Reduction by 0.5% per year	-	Reduction by 0.5% per year	-	Reduction by 0.5% per year	-	Reduction by 0.75% per year

3.3. Data Used for Sensitivity Analysis for Batteries and Synthetic Fuel Imports

To address the uncertainty about the future, a sensitivity analysis was carried out for the cost assumptions in relation to synthetic energy carriers and stationary batteries.

The first aspect of the sensitivity analysis is the import costs of synthetic energy carriers (hydrogen, liquid fuel, and methane). The import of synthetic fuels depends on numerous cost factors. One main cost driver is the price of renewable electricity. As stated in [37], about 40% of the costs of the final product are defined by these costs, with an assumed production in North Africa. The process of electrolysis, which is the basis for all the synthetic fuels considered in this paper, accounts for a share of about 20% of the costs of the final product. In the case of gaseous fuels, the liquefaction and the storage of the fuel also account for a share of about 20%. Additional cost aspects are costs for engineering, labor, insurance, taxes, and transportation.

The price paths for the sensitivity analysis for hydrogen, liquid fuel, and methane are shown in Figure 1. Two potential pathways have been developed. For hydrogen, the price paths are quite similar. They reach nearly the same costs in 2050, at about 130 EUR/MWh. For liquid fuels, the costs in a path A are at 240 EUR/MWh in 2050, and at 140 EUR/MWh in price path B. The costs of methane are at 197 EUR/MWh and at 155 EUR/MWh (path B).

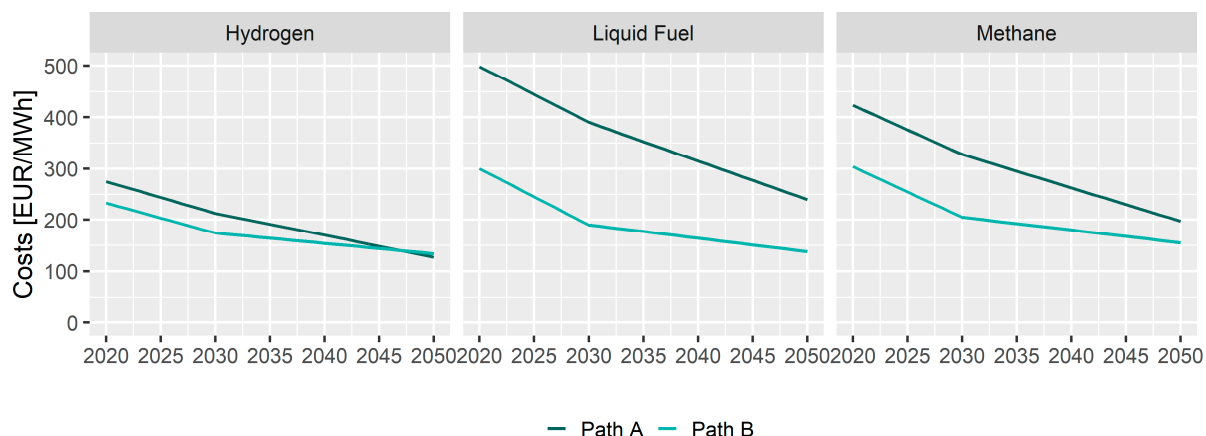


Figure 1. Different cost assumptions for the import of synthetic fuels, in EUR/MWh. The calculation of these costs was based on [37].

Due to the strong recent decrease in battery costs and further expectations of cost reductions, different pathways have been included. Figure 2 shows the different ranges compared to the reference value, which represents a medium baseline development. These cost developments are used in the sensitivity analysis for battery cost, varying the CAPEX between 50 and 250 EUR/kWh as target values for the year 2050.

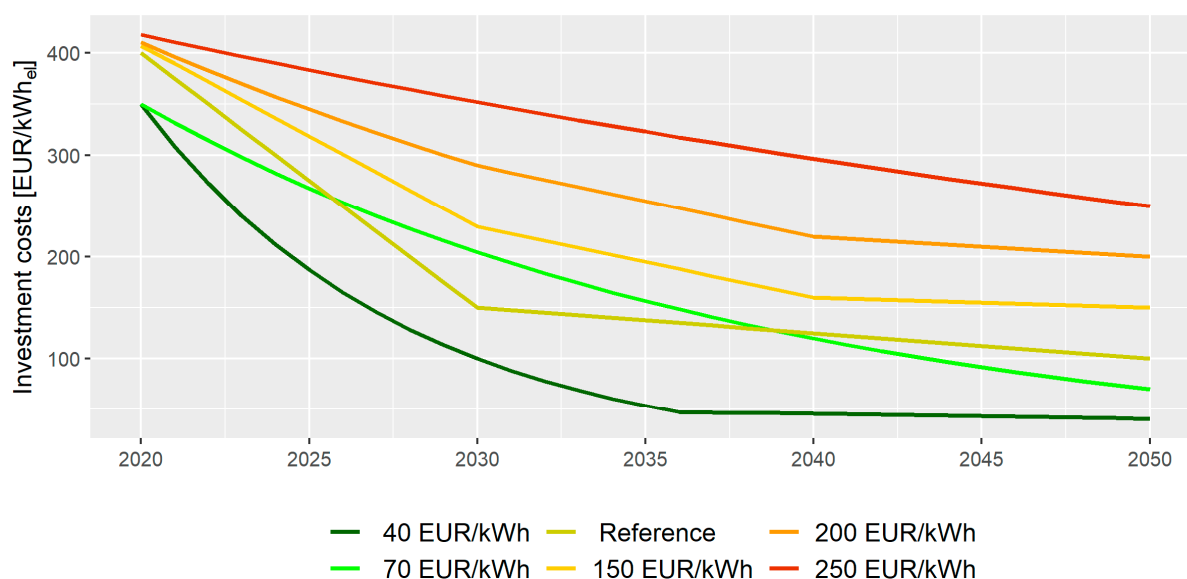


Figure 2. Variation of investment costs of stationary battery systems, in EUR/kWh (label corresponds to value in 2050).

4. Results

The model results, according to the scenarios defined in Section 3.2, are presented in Section 4.1. Section 4.2 illustrates the results of the sensitivity analysis.

4.1. Scenario Results for the Energy System

By the year 2050, the model indicates a major change in the energy supply and system structure in order to achieve an (almost) climate-neutral energy system in Germany. To show the changes caused by this transformation, in this paper we focused on the analysis of the development of energy flows in the energy system from the present to 2050.

A comparison of the structure of primary energy shows the shift from a fossil fuel-based system to a variable renewable energy (VRE)-based system, with contributions from energy sources such as biomass and environmental heat (see Figure 3). The total primary energy demand in Germany in 2018 was 3641 TWh, including a demand of 247 TWh outside of the energy sector. The final energy consumption was 2494 TWh, which is about 73% of the primary energy demand [38].

In 2050, all scenarios show a lower primary energy demand between 1700 and 2500 TWh, which is strongly linked to the assumptions of the scenarios. Additionally, with 84% to 92%, final energy consumption makes up a larger share of the primary energy demand. First, the shift from inefficient conventional power plants to VRE and second, the use of more efficient energy conversion technologies leads to this strong decrease in energy losses. The exact numbers vary between the scenarios. In the *persistence scenario*, the use of fuel-based technologies in the heat and transport sectors requires a higher supply of energy to capture the losses associated with the production of synthetic fuels used in fuel-based technologies, such as in fuel cell vehicles. As synthetic energy carriers are also produced using renewables, the total amount of renewable energy sources required in the *persistence* and *non-acceptance scenarios* are higher. The total capacity of renewables in Germany and abroad (for fuel imports) is the highest in this scenario. Therefore, their use in the *persistence scenario* requires the highest primary energy input.

In the *sufficiency scenario*, both parameters (primary energy and final energy consumption) are lower due to the reduction in consumption and the efficiency measures assumed here. The final energy consumption in the *sufficiency scenario* is only about 1500 TWh, compared to 2500 TWh in 2018.

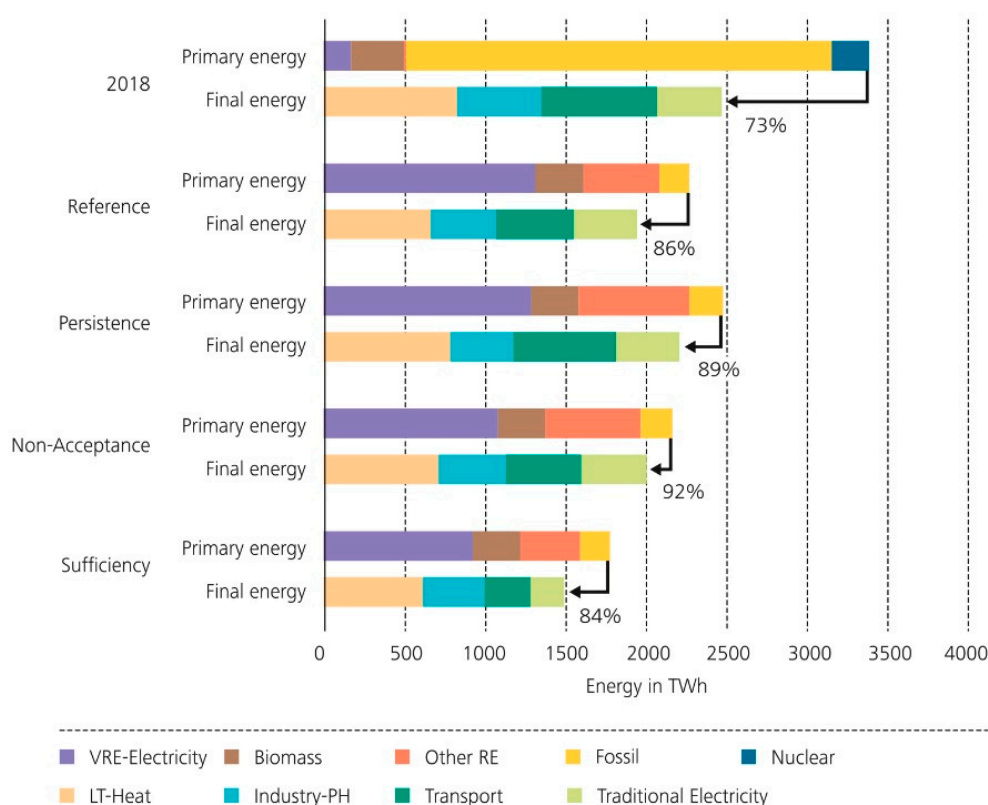


Figure 3. Primary energy and final energy in Germany for 2018 compared to four scenarios in 2050.

As electricity from VRE (wind and solar) is predicted to be the central primary energy source in the year 2050, electricity generation will obtain the most prominent role in a climate-neutral energy system. By the year 2050, electricity generation in Germany will be higher than today by a factor of 2.2 to 2.8 (dependent on the scenario) (Figure 4). The total installed capacity of VRE amounts to more than 500 GW_{el} in all scenarios. The installed capacity of VRE mainly depends on the final energy consumption, energy imports from abroad, and the efficiency of the technologies used.

The main reason for the increase in electricity generation is demand growth due to more sector coupling measures between the electricity sector and the heat, transport, and industry sectors, leading to the increased use of electricity-based technologies in these sectors. In relation to renewable energy, the contribution from conventional power plants is relatively small (~5–10% in 2050 in all scenarios with a mix of synthetic fuels and a small portion of conventional fuels). However, the installed capacity of all power plants operated with turbines is still found to be between 100 GW_{el} and 140 GW_{el} in 2050.

Consequently, the operating hours are low and focused on hours in specific days and weeks with very low generation from VRE sources. Energy storage measures, namely, battery storage, either in the form of stationary batteries or mobile batteries in cars, are chosen as the main short-term flexible option (see Figure 5). The model results in installed storage capacities of 100 to 400 GWh_{el} in 2050 in stationary batteries (in households and for grid stabilization) and an electrification of the private transport sector by nearly 80%, whereas today only a few GWh_{el} systems have been installed. As energy storage systems are linked with the use of other back-up capacities, Section 3.1 includes a specific sensitivity analysis of the costs of battery storages in the *reference scenario*.

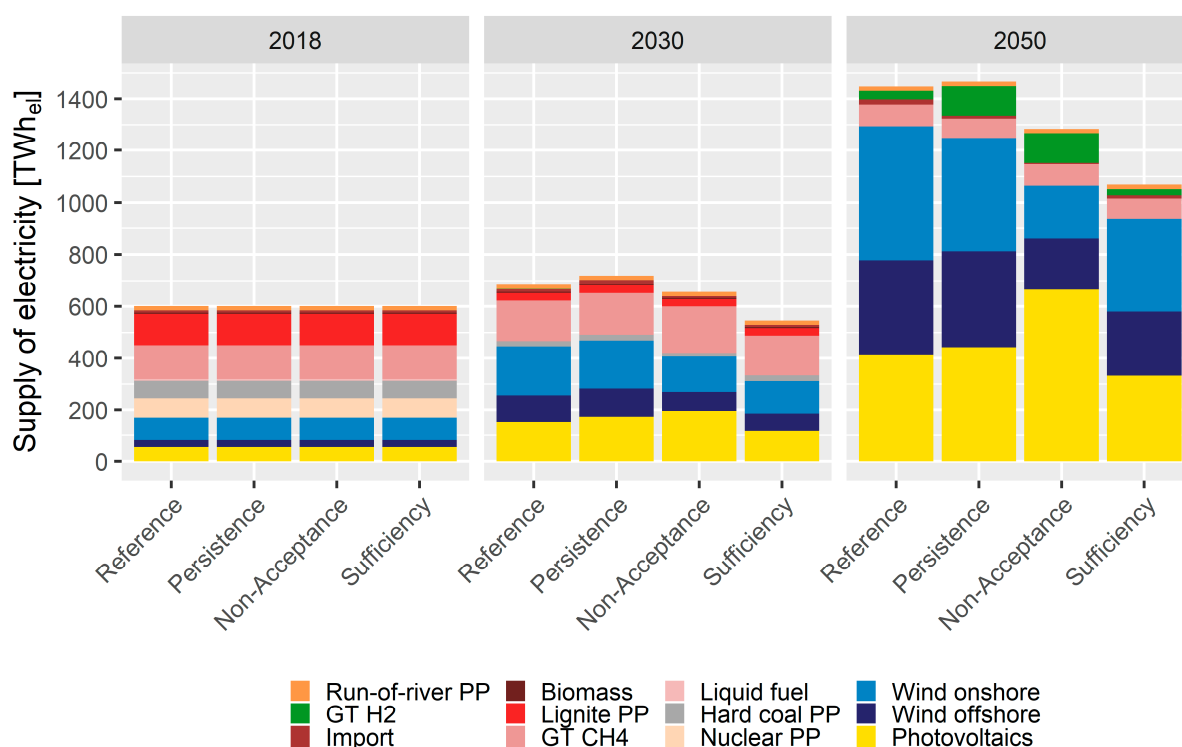


Figure 4. Electricity generation for 2018, 2030, and 2050 (results calculated with REMod).

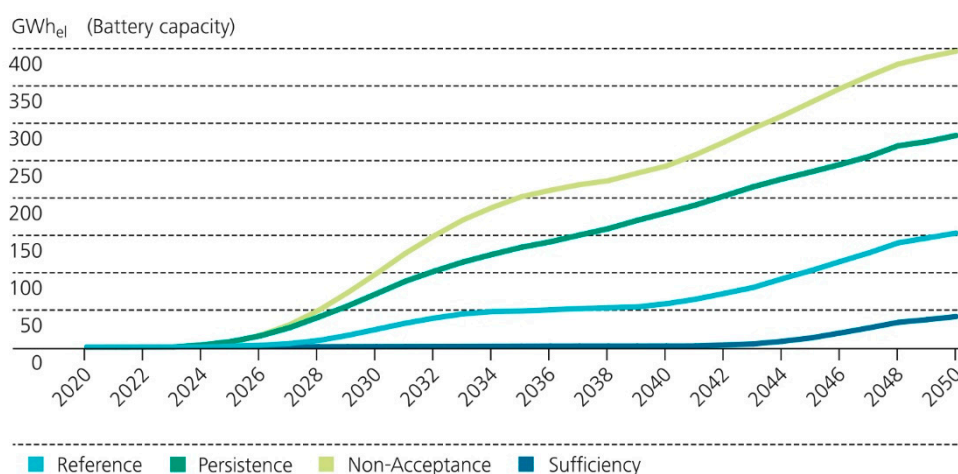


Figure 5. Installed capacity of stationary batteries in Germany for all calculated scenarios.

Figure 6 shows the development of electricity consumption, split by specific use, e.g., original electricity consumption; electricity for transport, industry, and heat; and power-to-X technologies such as hydrogen, methane, and synthetic fuel production. From today's electricity consumption of 550 TWh_{el}, this value strongly increases up to 1450 TWh in 2050, as a result of sector coupling activities, as well as power-to-X production. Issues such as export, transport losses, and curtailment are also increasing compared to the current energy system (summarized under "others"). In the *sufficiency scenario*, consumption reduction and efficiency measures still lead to an increase in electricity consumption due to more sector coupling, although the overall electricity demand is only about 1000 TWh. Again, the main difference between the scenarios is the amount of synthetic energy carrier conversion. Especially in the *persistence scenario*, the electricity demand for methanation is exceptionally high. Due to the tendency of using conventional gas boilers and combustion

engines, the way to reduce CO₂ emissions is to produce a carbon-neutral energy carrier for these technologies.

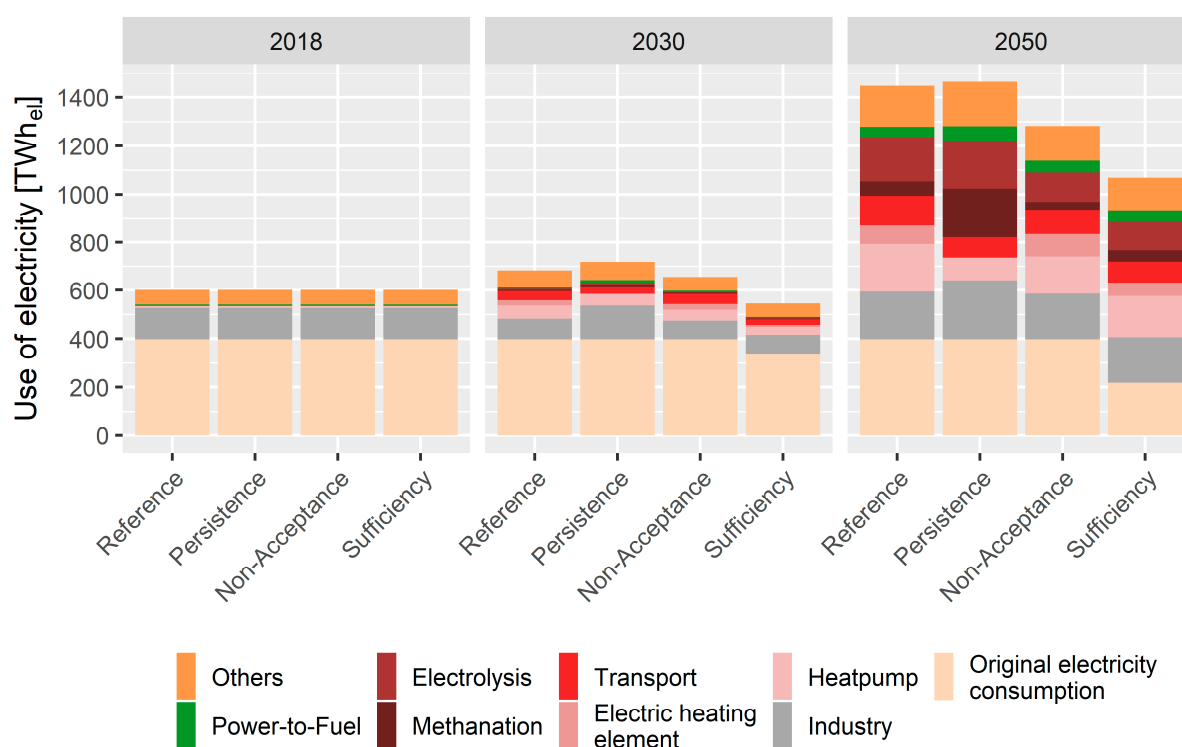


Figure 6. Use of electricity for 2018, 2030, and 2050 (results calculated with REMod).

For a scenario approach within a societal context, this indicates that a main difference lies in the use of power-to-X technologies. In the following sections, the analysis focuses on the split of energy carriers in each consumption sector, as these carriers are often linked to power-to-X technologies or usage.

The sector with the highest final energy demand is the building heating sector, with its millions of different buildings in terms of age, size, and structure. In the *reference scenario* and the *sufficiency Scenario*, district heating and heat pumps are the main applications used to supply heat in buildings (private, public, and commercial) in 2050. Methane and hydrogen could play minor roles in 2050, dependent on the scenario. However, today's widespread use of oil, natural gas, and biomass in the heating sector is predicted to be almost completely reduced by 2050, starting as early as 2030.

In the *persistence scenario*, the assumption of a 50% market share of conventional boilers requires a large amount of (synthetic) methane and hydrogen. In the *non-acceptance scenario*, the reduced wind power generation limits the use of electricity for building heating, but it increases the use of hydrogen, as it can be stored over longer periods, for example until the following winter (see Figure 7).

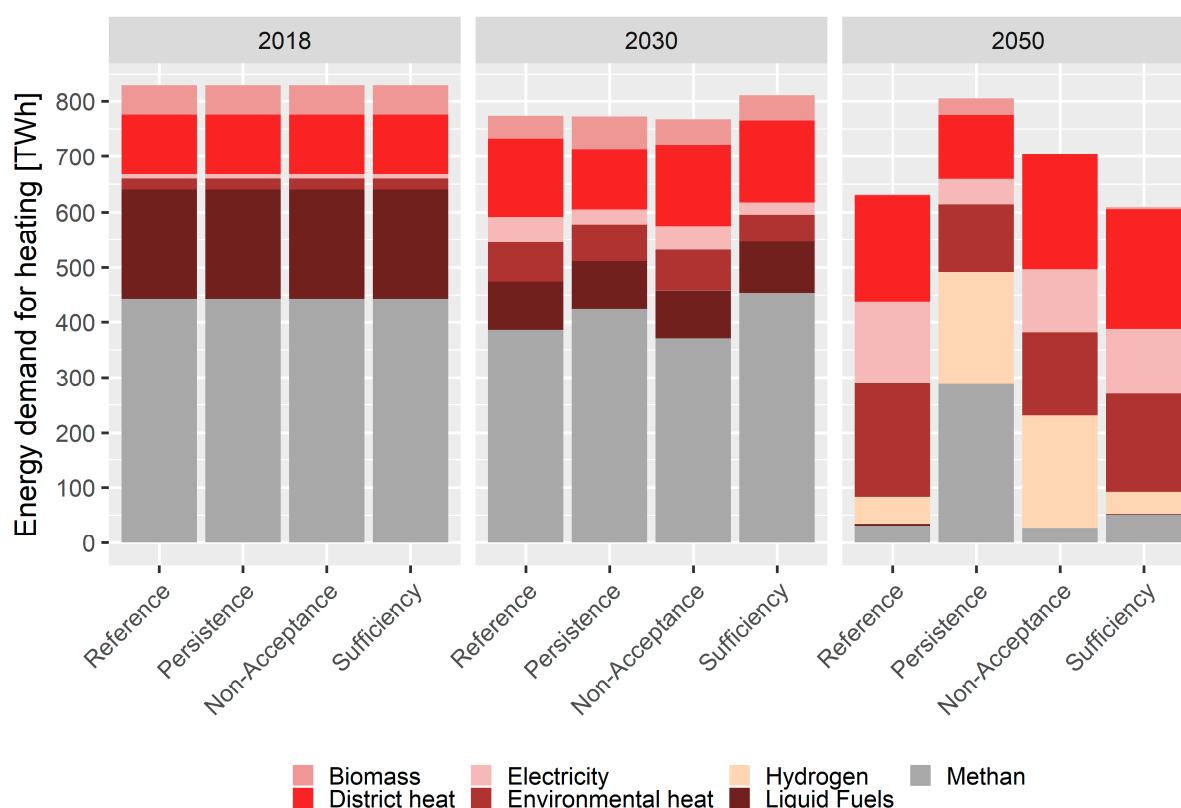


Figure 7. Present and future energy carrier mixes for building heating for the defined scenarios (results calculated with REMod).

In the industry sector, the analysis shows smaller differences between the scenarios (see Figure 8). The most commonly used energy carrier is electricity in process heating applications. Consequently, a high electrification rate is observed in the industry sector for all four scenarios. Nevertheless, the results in 2050 are only slightly sensitive to the scenario settings in the industry sector. Hydrogen is (compared to today) one new key element, as it can be used directly in some processes (e.g., the steel sector). It is assumed that coal will remain in the steel sector to some extent. Overall, the final energy demand in industry is reduced to below 400 TWh in all scenarios by 2050.

In terms of reduction of final energy consumption, the transport sector shows the largest reduction of all sectors due to the much higher efficiency of electric vehicles compared to fuel-based vehicles (see Figure 9). Only in the *persistence scenario*, with its high share of synthetic fuels, is this not valid. By 2050, the final energy consumption in the transport sector decreases to a level between 300 and 470 TWh if electric vehicles become a key technology, representing more than 80% of the overall vehicle fleet (*reference*, *non-acceptance*, and *sufficiency scenarios*). Although the switch in the passenger car stock is mainly from fossil fuel-based combustion engines to battery electric cars, the switch in freight transport is based on a combination of synthetic fuels and overhead line trucks. In combination with hydrogen (trucking and logistical applications) and synthetic fuels for aircrafts and other heavy transport applications, the transport sector shows a strong change in the applications and vehicles used. However, the *sufficiency scenario*, with shorter distances for travel and transportation, could lead to a much lower demand for energy in the transport sector. In contrast to this scenario, persistence in the transport sector leads to a high demand for (synthetic) liquid fuels.

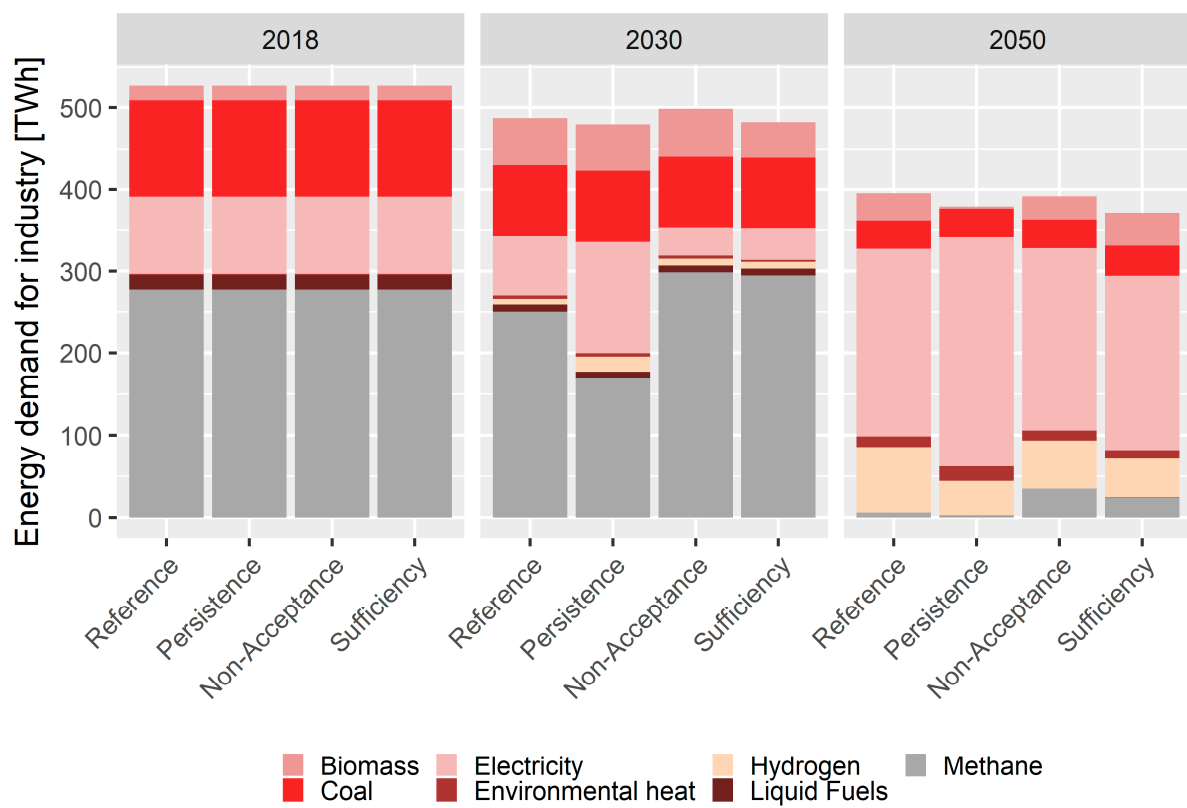


Figure 8. Present and future energy carrier mixes for process heating for the defined scenarios (results calculated with REMod).

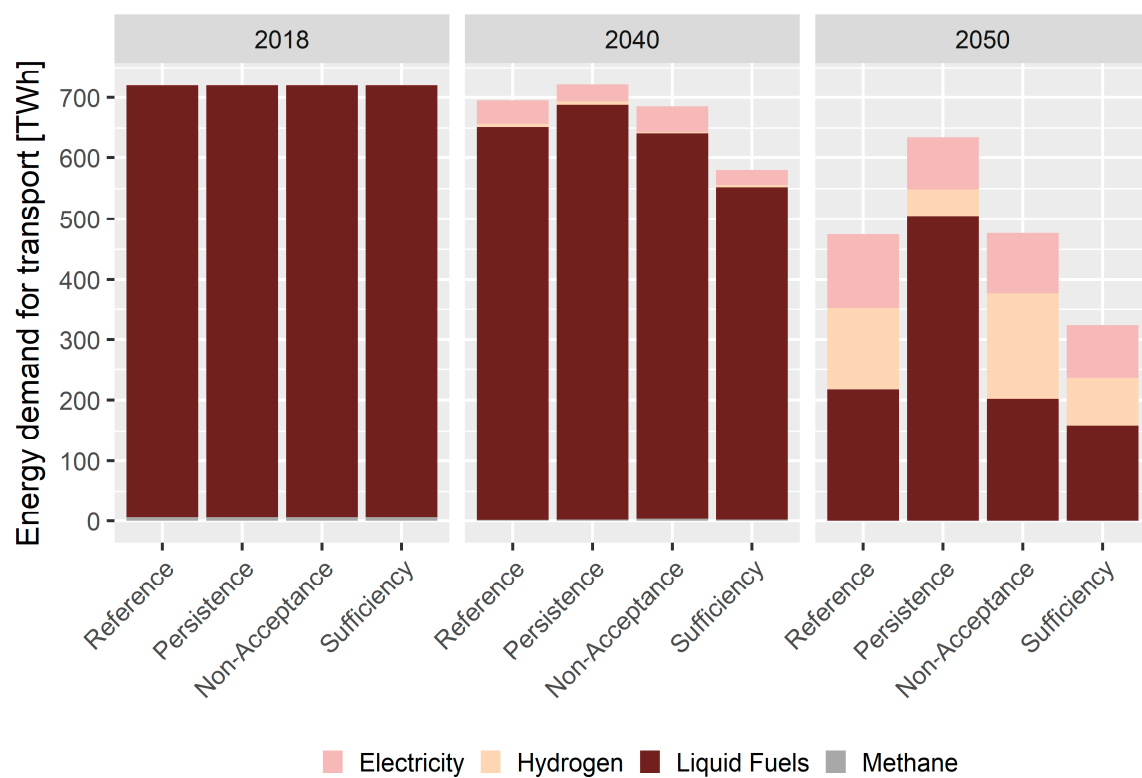


Figure 9. Present and future energy carrier mixes for transportation for the defined scenarios (results calculated with REMod).

These synthetic liquid fuels are also imported from other countries, as it is expected to be cheaper to import some of these fuels from countries with better VRE production capabilities than to produce them in Germany. Furthermore, as described by the transformation paths above, national electricity generation is already expected to reach its limits, due to an assumed maximal annual expansion of 15 GW_{el} of PV_{el} and 8.5 GW of wind within Germany. This energy is not sufficient to produce the amounts of imported synthetic fuels (depicted in Figure 9). Figure 10 shows the model results for the volume of imports. The comparison of imported synthetic fuels is very interesting, since the quantities vary a lot between the scenarios. In 2050, the *persistence scenario* requires a combination of 170 TWh of hydrogen and 350 TWh of liquid fuels. In the *non-acceptance scenario*, the hydrogen import is about 300 TWh, whereas in the *reference* and *sufficiency scenarios* it is between 50 and 150 TWh. The non-acceptance of large infrastructure in Germany leads to a higher share of hydrogen imports, as national electricity generation is limited by lower wind power expansion due to the non-acceptance of projects. Meanwhile persistence in terms of building renovation, heating technologies, and transportation leads to much higher importing of liquid fuels. Sufficient consumption behavior necessitates only small amounts of imported synthetic energy carriers.

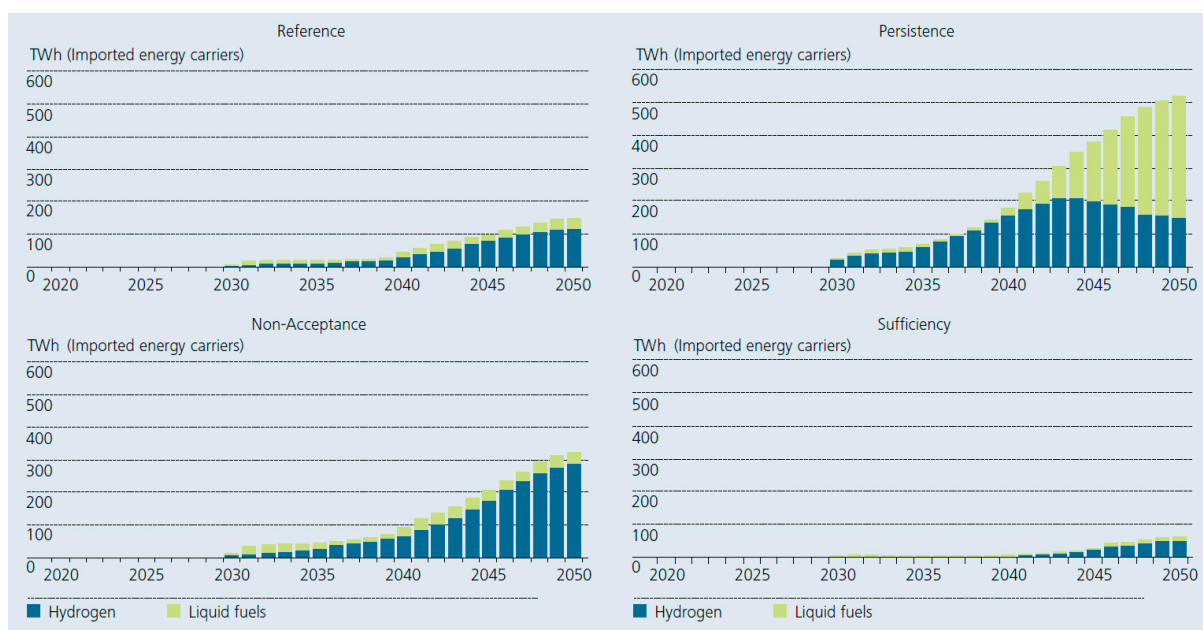


Figure 10. Imports of synthetic fuels generated using green electricity from solar and wind power at sites with high irradiation resources (source: [7]).

As the price path for synthetic fuel imports depends on multiple aspects, such as production costs, transport costs, and the costs of liquification, a specific sensitivity analysis, outlined in Section 4.2, focused on the impact of other price paths of the imported energy carriers.

The total system costs for the energy transition, calculated in REMod, vary strongly between the scenarios. Tendencies such as persistence and non-acceptance require much greater efforts to achieve the energy transition. The total system costs increase in both scenarios by 50% compared to the *reference scenario*. In the *sufficiency scenario*, costs decrease by 30% due to lower energy demands. The main cost driver is the huge import volume of synthetic energy carriers, which is calculated to be more expensive compared to the direct use of electricity. However, the demand reduction based on sufficient behavior is not priced. Therefore, this enormous reduction in final energy demand would lead to lower investments and operating costs in all sectors (e.g., a reduced number of cars).

4.2. Sensitivity Analysis

The aspect of uncertainties on future developments is addressed through a twofold sensitivity analysis, using different cost assumptions for the importing of synthetic fuels and for stationary batteries. As shown in Section 4.1, the imported volume of synthetic energy carriers and its composition varies between the considered scenarios. Still, with the exception of the *persistence scenario*, where liquid fuel technologies are forced into the system, in all other scenarios hydrogen is the main imported energy source by 2050. Figure 11 shows the amount of imported synthetic energy carriers and different import price developments for the years 2030, 2040, and 2050 for all four scenarios. Due to the strong decline in the cost of liquid fuels, this energy source replaces hydrogen as the main imported synthetic energy carrier in scenario sensitivities with price path B. According to the parametrization of the model, the importing of synthetic energy carriers is possible from 2030 onwards. Thus, from 2030, the import of synthetic energy carriers starts at a low level and makes a relevant contribution to the reduction of CO₂ emissions from 2040 onwards. All scenarios, except the *sufficiency scenario*, lead to an increase in the imported volume from 50 TWh (*Reference_B*) to about 300 TWh (*Persistence_B*) compared to the original values with price path A. By 2050, the *reference scenario* shows the largest increase in the imported volume, with a value of about 380 TWh (price path B), compared to 130 TWh in the study results. Price path B, in which only the cost of liquid fuels drops and that of hydrogen does not, shows that the *reference scenario* is most strongly influenced by the shift in the cost ratios between the different energy carriers. Still, the highest volume of hydrogen import is found in the *non-acceptance scenario*. In the *persistence scenario*, the imported volume increases to about 750 TWh, following price path B. The lower costs in this scenario show that comparable costs for hydrogen, liquid fuels and methane lead to the replacement of hydrogen imports by liquid fuels on a large scale. This can be explained by cheaper investment costs for liquid fuel-based technologies and thus with the possibility of reducing CO₂ emissions with existing technologies such as gas boilers and internal combustion engines.

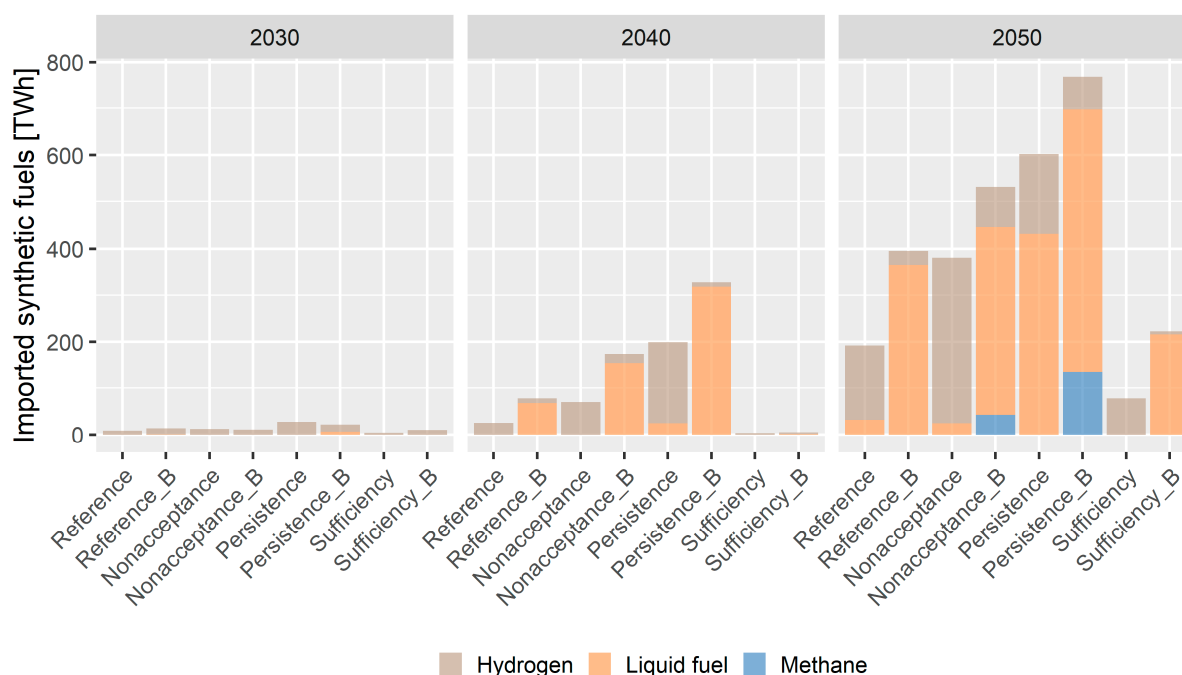


Figure 11. Imported synthetic fuels for the years 2030, 2040, and 2050, in EUR/MWh, for all scenarios of the study and for each the two cases.

Except for a decrease in specific costs per kWh for synthetic fuels, the total cost of importing synthetic fuels is predicted to increase due to an increased import volume. This changes the energy system composition in order to reach its cost optimum. Most affected by this adaptation are the energy converters for synthetic fuels, such as electrolysis, methanation, and the production of synthetic liquid fuels.

In the *reference scenario*, converter technologies have a share of about 20% of the total electricity demand by 2050. A reduction of the installed capacity of these technologies leads to decreased electricity demands. Even lower costs and an increased import volume of synthetic fuels cause an increased use of synthetic fuels in the transport, industry, and heating sectors. This also reduces the electricity demand. As a consequence, less installed capacity for variable renewable energy sources is required in order to cover the electricity demand in all scenarios. In total, the decrease varies between about 100 GW (*reference*) and 150 GW (*persistence*) in price path A. As a result, the installed capacity in the *reference scenario* reaches about 570 GW. This emphasizes that the costs of the importing of synthetic fuels do have a significant impact on the overall cost-optimized system configuration, and that VRE systems react very sensitively to the cost variations of synthetic fuels imports.

In a further sensitivity analysis, the specific costs of stationary batteries were varied in a range from 40 to 250 EUR/kWh in 2050. The results show that the costs of stationary batteries have a significant impact on the installed capacity (see Figure 12). The capacity varies between 30 GWh and 380 GWh in 2050 in the most extreme cost assumptions. In the range of 70–150 EUR/kWh, the results are comparably robust and vary from 160 to 190 GWh_{el} storage capacity (these values are similar to the assumptions in the *reference scenario*). However, the effects of the number of batteries on the overall system are quite limited; hence, the changes in building heating and tap water, as well as in the transport sector, are of negligible magnitude.

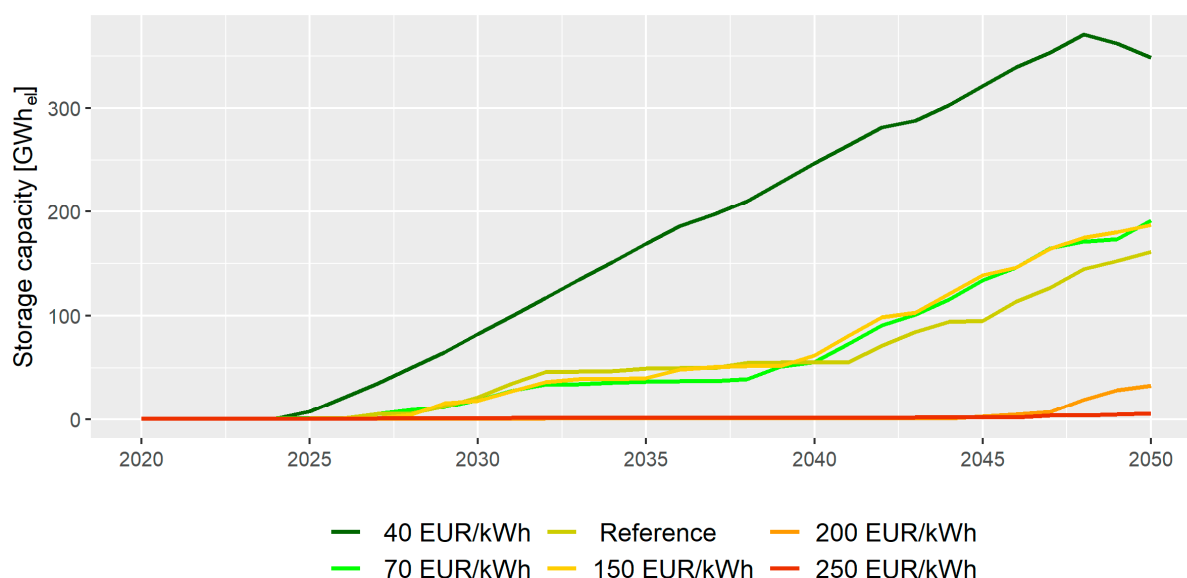


Figure 12. Installed capacities in the calculated scenarios.

4.3. Discussion of Results

The scenario approach using different storylines, such as persistence, non-acceptance, and sufficiency, generated strong differences in the results for all energy sectors, as well as in the required volume of electricity generation from renewables and synthetic energy carriers. In contrast to a technology-based scenario approach (e.g., “renewable energy world”, “efficiency”, “electrification”, or “hydrogen”), the scenarios, which were based on a technical, societal, and political context, show sector-overarching results and profound transition pathways up to 2050, especially when a balanced portfolio of technologies

and applications are used to reach a climate-neutral energy system. The results in all scenarios are based on a strong mix of technologies. However, each storyline and its context are directly characterized by specific choices in relation to different solutions. In all scenarios, a strong expansion of renewables is the basis for reaching a climate-neutral energy system. Especially in scenarios with strong limitations (e.g., due to tendencies towards persistence and non-acceptance in society or in certain investor groups), the possibility and responsibility to achieve a carbon-neutral energy system is partially shifted to other countries, with the expectation of high amounts of imported (CO₂-free) synthetic energy carriers or electricity. This creates a dependency on neighboring countries and their efforts to achieve a climate-neutral energy system. Consequently, national societal limitations are also balanced, with externalities in other countries. Volumes of 300 to 600 TWh (or even more) of synthetic fuels imported to Germany lead to installations of renewables in other countries of 200 to 400 GW, which is two to four times the capacity installed today in Germany (and is in the range of the total European solar and wind capacity in 2019). With energy imports from renewables and synthetic fuels, externalities such as land use, water availability, grid infrastructure, etc. are exported to other countries. Additionally, today's externalities (CO₂-emissions, health impacts, etc.) that arise from the use of fossil fuels are not considered and externalities should be analyzed in the evaluation of technology options. Assuming an increase in environmental awareness and therefore the adoption of more sufficient lifestyles, both the externalities caused by imports and the overall system costs can be kept lower than in the comparison scenarios. Nevertheless, for the assumption of a reduced energy demand in all sectors in the *sufficiency scenario*, a change in individual lifestyles, for example in consumption behavior, would be inevitable. Additionally, the transition paths with greater amounts of imports relate to higher total system costs.

Certainly, the calculated scenarios are only a few possible options for the development of the future energy system. The main differences in the social context (persistence, non-acceptance, sufficiency) can be coupled or weighted differently in other transition pathways.

However, this paper provides a perspective on how these three options with their explicit assumptions may influence the four demand sectors. As the results indicate, the structure of each sector can react strongly to these options.

In combination with the scenario assumptions, the technology and price assumptions are responsible for different pathways within each technology. In this paper, sensitivities were analyzed for synthetic energy carriers and stationary batteries. The authors have gathered the cost assumption data for Germany over many years. Before this publication, discussions and workshops with technology experts were carried out to include the latest updates (e.g., for electric vehicles). However, the prognosis of the cost assumptions for some technologies that show enormous market dynamics (e.g., battery prices) or other technologies that are in an early stage of development (e.g., technologies in the hydrogen and synthetic fuel value chain) also create uncertainties for the results of the transition pathways. Nevertheless, the sensitivity analyses show that, for example, a variation in costs for stationary batteries has a relatively small effect on the overall results, whereas the costs of the importing of synthetic fuels influence the structure of the whole energy system strongly.

It is not only in terms of cost (e.g., for batteries), but also in terms of availability (e.g., wind power) or technical characteristics (e.g., temperature levels) that many technologies interact with each other. The REMod model is designed to find a cost optimum between many technologies and all sectors. For example, a technology such as vehicle-to-grid can play a stronger role, as it is assumed that only 10% of car owners will provide the battery of their cars as flexible load for the electricity grid at the same time. An increase in shared battery use would directly reduce the use of stationary batteries. Similarly, direct interaction between the sectors might be realistic as markets (or systems) are directly or indirectly distorted by market frameworks or other regulatory boundaries. However, the

model results show that short-term flexibility is required (e.g., stationary batteries are needed if V2G is limited) and strong linkages between sector measures are necessary as the decarbonization of one sector influences the other sectors as well.

5. Conclusions

This study shows the influence of some societal aspects on a long-term energy transition. The development of most energy system models focuses on the reproduction of technical aspects, and social aspects are often not considered. Therefore, consistent storylines expressing societal behavior, such as persistence in the use of conventional technologies such as combustion engines or gas-boilers, non-acceptance of infrastructure measures such as wind power plants, or more sufficient behavior, with a reduction in the useful energy demand for the first time, are integrated in the parametrization of an energy system model. By using the REMod energy system model, which optimizes all sectors of the energy system, a holistic view on the impact of social behavior on the development of the energy system was created.

Based on the analysis, the clear conclusion is that the target of a climate-neutral energy system can be achieved by 2050 under technical, societal, and political constraints, which are considered in four scenarios, whereby in each case different efforts have to be undertaken to fulfil the transition.

Electrification is the key to decarbonize all sectors, as this is the most efficient direct use of renewable energy, which is mainly generated from solar and wind (especially in Germany). With the REMod energy system model we have shown how the integrated sector-coupled approach to the energy system leads to a high use of sector coupling technologies that use electricity directly (such as electric vehicles with bidirectional charging or heat pumps) and indirectly through chemical energy carriers.

However, the scenario approach, with societal trends representing the key differences between the scenarios, shows a strong impact on specific solutions in the energy transition. Trends will have a dramatic influence on the resulting energy demand, applied technologies, and applications. In the *reference scenario*, an optimized system is well-balanced between various options. The scenario uses wind and solar as the most important electricity generation technologies, batteries as a flexibility option, small shares of local and imported synthetic fuels, and a combination of technologies in the demand sectors. The stronger limitations in the *non-acceptance scenario* and the *persistence scenario* lead to more installations (e.g., of variable regenerative energy technologies) or imports. For example, more solar plants have to be installed if wind power plants are not accepted, or more synthetic fuels have to be imported if heat and transport sectors switch less to electricity or hydrogen-based technologies. Both scenarios are hence associated with a greater effort required for society to achieve the climate goals. On the other hand, the transition can be carried out more easily if sufficiency becomes an overall strong trend. An extensive demand reduction due to sufficiency will require less effort for the transition in the field of energy. Therefore, societal trends such as persistence, non-acceptance, and sufficiency are recommended to be considered during the prediction process for long-term transition pathways for the energy system. In this paper, it is also shown that the price and availability of synthetic fuels influence their use strongly. Low prices and high import potentials are both necessary for synthetic fuels to be a keystone in a future energy system. However, both are associated with high uncertainty. Compared to this, the price of batteries in the considered range does not impact their deployment and use. Short-term energy storage and flexibility (as provided by batteries) in the electricity system is always required on a very stable GW-scale.

Although the storyline-based approach for the integration of social behavior provides a good impression of how these aspects influence the energy transition along with technical aspects, the parametrization of the energy system model is dependent on the assumptions made. This is caused by a lack of literature on the impact that different social or political decisions have on the expansion of specific technologies. To develop a more scientific basis for the integration of social aspects in energy system models, further studies, for

example, on the reasons why consumers are for or against specific technologies, would be helpful. Furthermore, the model used is a technical bottom-up model which involves the optimization of the total energy system costs. To address social behavior more accurately, an integration of consumer decisions in energy system models would improve the assessment.

As the sensitivity analysis of the import costs of synthetic energy carriers and stationary batteries shows, specific parameters have a strong impact on the transition pathways. Although minor variations in the costs of stationary batteries have only a low impact on the results, small changes in the costs of imported, carbon-neutral energy carriers have a strong impact on different aspects of the energy system transition. Therefore, it is crucial for further studies on transition pathways to identify the parameters with a large impact and high uncertainty and to consider them in the sensitivity analysis.

Nevertheless, the combination of consistent storylines about social behavior with a holistic energy system model such as REMod could also be applied to countries other than Germany. This method would be especially interesting for countries with an ongoing social transition and a strong increase in GHG emissions. For this purpose, the storylines would be different, as the starting point of the transition, for example, for emerging countries, would not be the same as that found in an industrial country. An additional challenge would be the huge amount of data necessary to apply a holistic energy system model to a new country. However, by considering social aspects in energy system models, it can be emphasized that the transition of the energy system can go hand in hand with a high standard of living. For the use of the methodology in different regions or countries, the following implementation steps must be undertaken:

- (1) Definition of the specific energy system
- (2) Evaluation and implementation of the scenario settings, based on an analysis of ongoing societal trends in the specific location. This might require a detailed analysis of the literature to be able to include the relevant framework conditions and trends.
- (3) Data integration of the energy system and the specific scenario settings (here, tests and validation processes are required).
- (4) Application of the model and analysis of the results.

In the case of the German energy system and its transition to a low-carbon system, the following points can be concluded from a systemic and cost-optimal view:

- Primary energy demand and final energy consumption will decrease due to a high share of efficient electricity use;
- Large amounts of renewables are required to transform the system from a conventional fuel-based system to a system with almost zero carbon emissions;
- The rate of transformation in industry, buildings, and transport is high, as the used technologies are almost completely replaced (e.g., oil/gas boilers to heat pumps; except in the *persistence scenario*);
- Short-term flexibility options, such as stationary batteries and heat storage, including a charging strategy for electric vehicles or the adaptable operation of heat pumps, are necessary;
- Synthetic energy carriers (mainly hydrogen synthetic liquid fuels) are necessary for heavy transport and other mobile applications, as well as for CHP plants and high-temperature process heating; they are partly produced in Germany and the remainder are imported from other countries, if available.

To reach climate neutrality, a few societal, context-based pathways have been described that either impede or ease the achievement of climate protection goals. There is still a long way to go and it requires major efforts, many different measures, and a mix of technology strategies.

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Nomenclature

BEV	Battery electric vehicle
CAPEX	Capital expenditures
CIB	Cross-impact-balance analysis
CO ₂	Carbon dioxide
e.g.,	Exempli gratia
EUR	Euro
G2V	Grid to vehicle
GDP	Gross domestic product
GW	Gigawatt
GWh	Gigawatt hours
ICT	Information and communications technology
kWh	Kilowatt hours
NECP	National Energy and Climate Plan
NIMBY	Not in my back yard
PV	Photovoltaics
SAS	Story and simulation
TWh	Terawatt hours
V2G	Vehicle to grid
VRE	Variable renewable energy

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