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ABSTRACT

The energy transformation requires a shift in the energy sector from fossil fuels and their related technologies to carbon free technologies which are mainly renewable energy technologies. In addition to them, three key elements foster the realization of smooth and stringent transformation paths: coal phase out, energy efficiency, and electricity exchange. By applying the techno-economic energy system model REMod-D, the German case is analyzed in this paper with a focus on effects created by emphasizing these three elements in an energy transformation strategy. The analysis covers their impact on the power sector, heating sector, and transport sector which are influenced by the actual shaping of these elements. Overall, the model results show a shift in the German energy system towards a system using more electricity. This electricity is generated up to 85% from photovoltaics, wind power, and other renewable energy sources. Each of the three elements, if employed, leads by itself to a reduction of efforts on the level of developments such as the deployment of renewable energy and renovations, as well as the electrification of vehicles. In the case of combining the three elements, complementary effects can even be summed up. In the Active scenario with a joint use and implementation of the three key elements, this combination is analyzed as part of a cross-sectoral energy strategy for the transformation. Each element can reduce the total system cost by around 16 billion EUR per year. This paper concludes to prioritize these three key elements in the energy strategy in addition to the strong expansion of renewables and the change of heating systems and vehicle concepts.

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I. INTRODUCTION

The efforts to reduce climate change until 2050 within the Paris Agreement for nationally determined contributions are challenges for energy systems as they include a transformation from a mainly fossil fuel based system to a renewable energy based system within the next 35 years.[1] For countries such as Germany, central drivers are necessary to facilitate the energy transition. Of course, the role of renewables will be prominent as main energy suppliers of CO_2 emission free electricity which is generated from sun, wind, water, and biomass.[2,3] Several studies have shown a massive expansion of renewable energy technologies not only in Germany but also in all European neighboring countries to reach climate targets.[4–8] However, recent studies also have clearly shown that replacing electricity produced with fossil energy sources by renewable energies will by far not be sufficient to achieve climate targets by itself.[9] In fact, many end-use sectors which today are dominated by fossil energy sources must be shifted to increase the use of electricity either directly or indirectly, i.e., coupling of the energy sectors (electricity, heat for buildings, heat for industry, and transport) is highly necessary to reduce CO_2 emissions in all energy sectors.[10,11]

Widely used methods in the field of applied energy economics are equilibrium or partial equilibrium models and simulation approaches to analyze long-term developments in the energy sector or in the total economy including the energy sector.[12–15] For macroeconomic problems (e.g., demand or portfolio developments), large models are developed such as GEM-E3 by the European Joint Research Center[16] and NEMESIS.[17] Least cost optimization is also an often used method to analyze the sector specific developments in the energy sector. These optimization models are, e.g., MARKAL and TIMES[18] or EFOM (Energy Flow Optimization Model; see, e.g., Ref. 19). In contrast to optimization models, simulation methods can also be used, e.g., EneryPLAN simulates the energy balance on an hourly basis.[20] The simulation and optimization model REMod is somehow between these approaches as it simulates the hourly operation of the electricity, heating, and transport sector in a single model approach (by using many links between the sectors). However, it also optimizes the simulation runs in order to obtain a least cost transformation path from today (2015) to 2050.[21]

In the following tables, recent studies on the German energy transition are compared qualitatively and quantitatively. Table I shows the objectives and results of these studies and their main statements regarding the characteristics of transformation paths and the role of sector coupling. Table II compares the main quantitative results for specific parameters in each study: primary energy demand, role of power-to-heat, power-to-gas, and power-to-liquid, as well as role of renewables (namely, photovoltaic (PV) and wind).

However, these studies and their scenarios have used very different assumptions for some key elements within the energy system: Demand development, use and role of biomass, coal phase-out, and energy exchange with neighboring countries (imports and exports).

Demand development and efficiency measures in all energy sectors have a large influence on the required amount of renewables and other fuels in a future energy system. Furthermore, the uncertainty on future energy demand is quite high due to several reasons. Potential new applications with additional energy demand (e.g., digitalization and new electronic devices) will change the consumption of energy in the future. On the other hand, efficiency measures in the heating or transport sector can also reduce consumption or vice versa will lead to rebound effects with an increase in comfort or travel kilometers of passengers.

The way of phasing-out coal-fired power plants (hard coal and lignite) is up for discussion in Germany, also due to the linked economic and socio-economic impact in specific regions of the existing power plants.[26] However, CO_2 emissions from coal-fired power plants are a large share of CO_2 emissions in the electricity system today, with still 224 Mio t tons per year.[27] A rapid phase-out path for coal and lignite could lead to a high reduction of CO_2 emissions in the energy system.

Another important contribution in a future energy system is the role of imports and exports, especially from electricity. With the exchange of intermittent generation from wind and solar, the cross border exchange of electricity will increase anyway in a system based on high shares of PV and wind power. However, good resources in other countries, e.g., wind in the North Sea or solar PV in Italy or southern France, can increase electricity imports from these countries. Therefore, decarbonization targets can also be reached by using potentials of renewables in neighboring countries.

To outline this paper, the objective is to compare in a scenario approach these three key elements (coal phase-out, energy efficiency, and electricity imports). It is assumed that nuclear phase-out takes place in Germany, but Carbon Capture and Storage (CCS) is not a solution. A quantitative model analysis is therefore provided by using the energy system model REMod.[6,28] Transformation paths until 2050 (as different scenarios) for the German energy system are analyzed with an integrated energy system which takes into account a strong sector coupling. The scenario approach in this paper includes a first scenario which does not force rapid progress in three key elements. Then, the three elements are taken into account separately (scenario 2 to 4). Finally, a last fifth scenario, called "Active," is shown which combines the three elements. Many assumptions and the first scenario are also published in the report "Sector coupling—analysis and considerations on the development of an integrated energy system" [German title: Sektorkopplung—Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems acatech—Sektorkopplung] published by acatech.[25]

II. METHODOLOGY

A. Modeling of the energy system with REMod

To evaluate potential structural options of the German energy system until 2050, a model-based analysis is carried out utilizing the simulation and optimization model REMod-D. The basic idea of the model REMod-D is a cost-based structural optimization of the transformation of the German energy supply system for all consumption-sectors—i.e., the sectors electricity, low-temperature heat (space heating and hot water), high-temperature (process) heat, and transport. The purpose of these calculations is to determine a cost-effective transformation path from the current system to an energy system in 2050, with a total annual upper limit of permitted CO_2 emissions across all sectors. The model calculations describe technically possible development paths of the energy system with all related system components (such as generators, converters, energy storages, networks, and car parks) and optimize them in terms of

TABLE I. Related literature on scenario pathways for German energy transition, based on Ref. 25.

Article/study	Authors/institutes	Contractor	Objective/research question	Transformation paths and sector coupling
Klimaschutzszenario 2050 (2. Endbericht), (2015),[22] engl. Climate Protection Scenario 2050	Öko-Institut, Fraunhofer ISI	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)	Compare different technical scenarios with different, specific ghg emission targets (−80%–95%), also including options for policy measures and corresponding economic effects	Increase of electricity based application, electrification in the transport sector, high share of heat pumps in heat supply, hydrogen production, and methanation is included
Treibhausgasneutrales Deutschland im Jahr 2050, (2014),[23] engl. Germany in 2050—a greenhouse gas-neutral country	Umweltbundesamt	Own research work	Illustrate different scenarios for Germany for complete ghg-neutrality	Strong focus on electrification, methanation, and the use of (imported) hydrogen as the main options
Interaktion EE-Strom, Wärme und Verkehr (2015),[24] engl. Interaction of RES electricity, heat and transport	Fraunhofer IWES, Fraunhofer IBP, IFEU—Institut für Energie- und Um-weltforschung, Stiftung Umweltenergierecht	Federal Ministry for Economic Affairs and Energy	Study of the power demand in a cost optimized, integrated energy scenario which includes all consumption sectors; ghg emission target of minus 80% in all sectors by 2050	High degree of electrification, high number of heat pumps, and strong use of district heating
BMWi Langfristszenarien[4] Engl.: Long-term scenarios	Fraunhofer ISI, Consentec GmbH, ifeu	Federal Ministry for Economic Affairs and Energy	Calculate several cost optimized scenarios with varying assumptions and different technology options to reach the German climate targets. A main focus lies on the transition costs, the role of renewables, and the consequences on the energy supply system.	High expansion RES, high electricity import from Europe, low capacity of flexible conventional power plants in Germany compared to today, and little use of PtL/PtG
Klimapfade für Deutschland,[5] Engl.: Climate paths for Germany	The Boston Consulting Group (BCG), prognos AG	The Federation of German Industries (BDI)	Transformation paths which are cost optimal and effective to transform the energy system under the constraint of the remaining German's industry structure and competiveness	Importance of electric mobility and heat pumps is highlighted, and sector coupling depends on the level of decarbonization (80% vs 95%)
"Sektorkopplung"—Optionen für die nächste Phase der Energiewende Engl. Coupling the different energy sectors—options for the next phase of the energy transition[25]	acatech, Leopoldina, Akademienunion	…	Illustrate different options for the energy supply system in Germany in order to reach the climate goals	High share of electricity in transport and heat sector (electromobility, heat pumps, and power-to-heat), consistent role of cogeneration plants, production of hydrogen, and synthetic fuels of high importance for long-term transition

minimizing the costs of the energy system based on the assumptions and the analysis frame. A detailed model description is given in Refs. 6, 21, 28, and 29.

Figure 1 shows the schematic structure of the illustrated energy system. The energy demand side (right) is divided into four utilization areas: transport, electricity, low-temperature heat, and process heat. The calculations assume the so-called "single-node model" or "copper plate model," in which the distribution of electricity is not subject to any restrictions, meaning each unit produced and each unit demanded are available in the time step considered throughout Germany. However, the necessary costs for the expansion or operation of the power grid are included in the cost accounting.

In REMod-D, various assumptions and simplifications are made when modelling the German energy system, for example, developments that are not subject to optimization are exogenous to the model. To better interpret the results of this paper, the most important assumptions are presented below:

- The driving boundary for the calculation of transformation paths is the maximum amount of energy-related CO_2-emissions permitted in each year.
- The maximum possible addition of implemented technologies is limited by year-end specified maximum expansion quantities. Due to production limitations, not any number of plants, such as wind turbines, can be built and then installed (see also Ref. 21).
- The electricity base load (from original electricity applications) in the model is based on the time series of the European Network of Transmission System Operators for Electricity and includes any electricity demand in Germany in hourly resolution, minus the electricity for room heating

TABLE II. Key results on the energy system in 2050 according to different studies, based on Ref. 25.

Article/study; scenario	Primary energy consumption in TW h	Final energy in TW h	Share RES in final energy	Gross electricity generation in Germany in TW h	Electricity consumption of PtH in TW h	Electricity consumption of PtL in TW h	Electricity consumption of PtG in TW h	Reduction of CO_2 emissions	Use of biomass (primary energy) in TW h	Installed capacity of PV/wind-onshore/wind-offshore in GW
Climate protection scenario 2050; Scenario KS 95	1696	1157	96,40%	769	16	129	43	−95%	1107	130/150/45
Germany in 2050—a greenhouse gas-neutral country	3086	1651	100%	3.086	76	548	110	−100%	198	275/~380/45
Interaction of RES electricity, heat and transport; cross sectoral target scenario	n/n	n/n	n/n	816	196	n/n	32	−80%	n/n	200/140/38
BMWi long-term scenarios; basic scenario	1923	1507	46% (of primary energy consumption)	501 (net electricity generation)	32	0	0	−80%	371	69/75/15
Climate paths for Germany; scenario: global climate protection G80	2146	1617	50% (of primary energy consumption)	626	n/n (but: 11 GW installed capacity)	0	0	−83%	345	105/97/47
Coupling the different energy sectors—options for the next phase of the energy transition; scenario open_85	2212	1800	Ca. 70%	1074	47	12	167	−85% (in the energy sector only)	293	254/212/33

and hot water. This electricity base load includes, for example, electricity for electrical rail transport, households, industrial processes, lighting, air conditioning, cooling supply, etc. In total, it results in an annual electricity demand 481 TW h in the start year (2013). Electricity for space heating and hot water is calculated endogenously and presents additional power consumption to the base load.

- The supply of electricity from run-of-river power stations is mapped to hourly resolution based on the data of the EEX transparency. The installed capacity of today's power plants is assumed to be constant over the observation period. Thus, there is no optimization of the installed capacity of run-of-river power stations.
- The share of all buildings that have a district heating connection is limited to a maximum of 25% in 2050. By comparison, today, district heating connections make up around 14% of all heat supply systems.
- Additional CO_2-emissions from non-energy related use of fossil fuels (e.g., steel production and chemical industry) are not taken into account.
- Electrolytic hydrogen production, production of synthetic fuels, and methanation are considered as options for Power-to-Gas and Power-to-Liquid applications.

Input data indicated above are required to calculate hourly energy balances and total system cost. Therefore, the model includes also cost assumptions, weather data, and energy load and production profiles. Although the model takes geographically resolved weather information into account, the energy demand, generation, and distribution are not spatially resolved. However, costs of necessary infrastructure (e.g., grid expansion) are considered by weighting factors for each application technology proportional to their expansion.

All in all, the REMod-D model is more detailed regarding the development of the energy system and the energy system cost for every consumption sector and energy source during the transformation path until 2050 than any known source to the authors. The depth of details is achieved by looking at the flow of energy on an hourly basis, subsequently ensuring secure energy supply to all consumers at any time between today and 2050. Furthermore, all technologies are optimized in parallel and in full dependency. Other models are either extended electricity models or do not apply a full optimization of all sectors or do not cover the full transformation path with regard to cover each hour by using different weather years at the same time. In this respect, despite the aforementioned uncertainties, the results provide a sound cost analysis for the transformation of the German energy system, which goes beyond previously available data and statements.

B. Data and scenario assumptions

In total, five different scenarios are compared in this paper: one reference scenario ("basic scenario"), three scenarios with each focusing on one key element (efficiency, coal phase-out, and electricity imports), and one scenario combining all three elements ("active scenario").

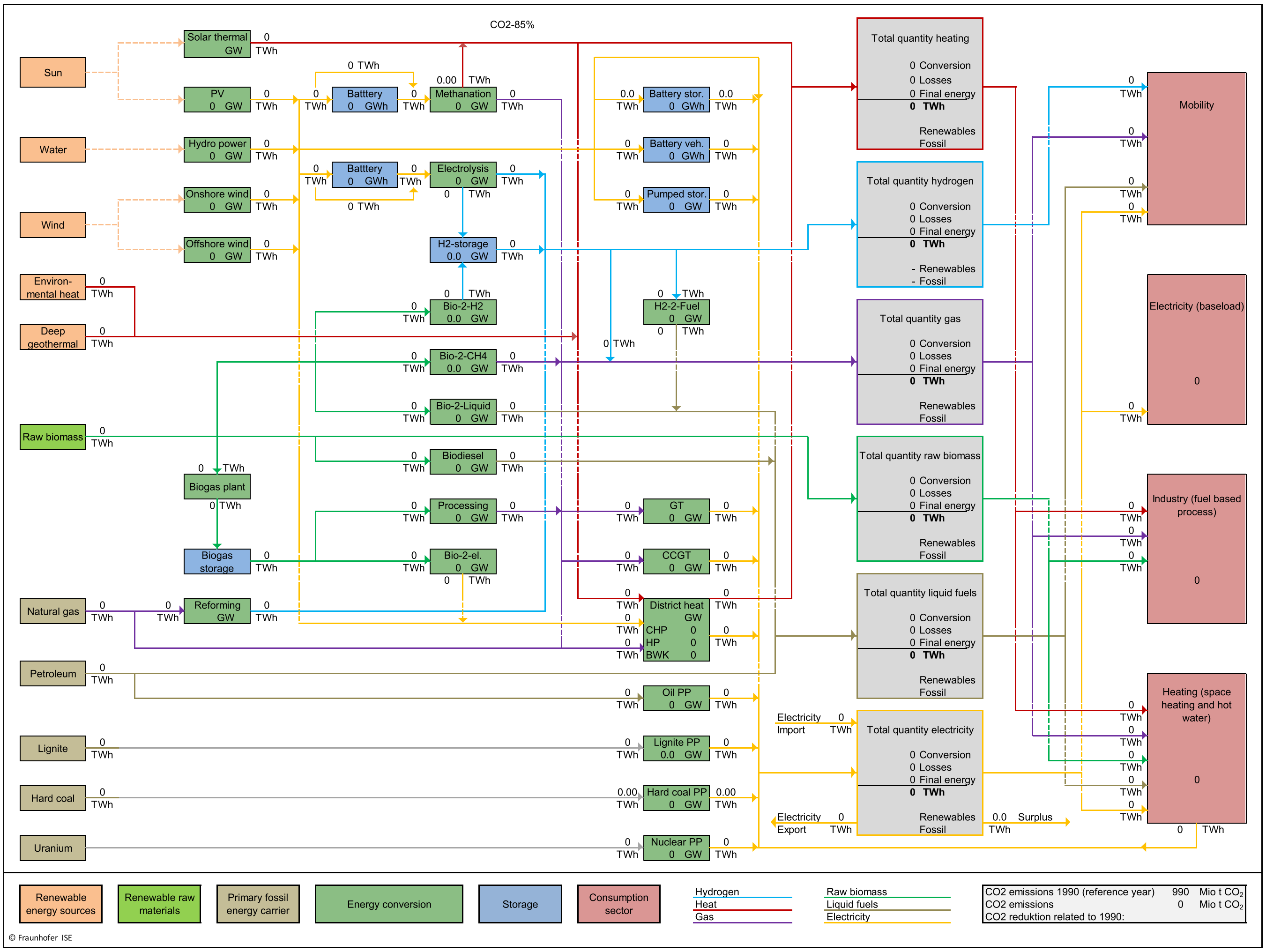

FIG. 1. Schemata of energy flows in REMod.

For the energy system analysis until 2050, the following projections and assumptions for a wide range of parameters are necessary. They are used in the **basis scenario** and other scenarios if not noted otherwise:

- The reference year for all CO_2 reduction values is 1990. CO_2 emissions are reduced continuously to −85% compared to 1990, by taking immediate targets for 2030 and 2040 into account.
- Financial burdens for CO_2-emissions are not considered in these scenarios. The allowed amount of CO_2 emissions is set as a hard annual limit, and the model guarantees strict compliance. [This corresponds to the approach of a CO_2 trading system with fixed caps. Exogenous defined CO_2 prices would comply with taxation of emissions. The model allows an ex-post calculation of the average abatement costs for the whole investigation period. An additional cost burden would not automatically lead to further emission reductions, only if the total cost would exceed the ex-post calculated average abatement costs.]
- The interest rate for annuity calculations is set uniformly at 8%.
- Energy prices for oil/gas and lignite/hard coal imports are assumed to be temporally constant (reference year 2016). [Cost assumptions for energy carriers are natural gas 33.1 €/MW h, oil 52.0 €/MW h, hard coal 16.0 €/MW h, lignite 1.5 €/MW h, biomass (wood) 50.0 €/MW h, biomass (cultivation) 50.0 €/MW h, and biomass (moist) 10.0 €/MW h.]
- The performance and capacity of pumped storage power plants remain on the present level.

- The total capacity of grid interconnections abroad remains constant at 15.5 GW.
- Solar thermal energy is not considered for process heat generation.
- Energy potential for biomass will remain constant on the present level at 293 TW h.
- Technical potentials for sun and wind were determined on the basis of the study "Treibhausgasneutrales Deutschland 2050."[23] It is assumed that 45 GW_{el} or 189 GW_{el} wind turbines at sea and on land, respectively, are possible and that around 300 GW_{el} of photovoltaic systems (including around 25 GW_{el} on open areas) can be installed. It is assumed that the number of buildings in Germany will increase from today's approx. 25.4×10^6 to 26.9×10^6 by 2050.[30] Additionally, every new building must have at least the refurbishment level "fully refurbished."
- The number of cars in the transport sector will decrease slightly from 47.8×10^6 today to around 45×10^6 in 2050. By contrast, the number of trucks will increase slightly from 5.1 to 5.4×10^6 in 2050.
- Coal and lignite power plants are considered with limited flexibility due to their role as combined heat and power (CHP) plant and based on operational constraints. Therefore, a certain share of the power plant fleet is considered as must-run capacity (decreasing from 50% to 0% in 2050).
- Demand for energy from aviation and shipping in Germany is assumed to be on a constant level from today. In addition, only liquid fuels are considered as energy carriers for this purpose.
- In industrial processes, the model assumes a conversion efficiency of 90% from final to useful energy. Industrial process heat is considered in the model as a constant hourly load. For process heat, only biogas and solar thermal heat can substitute fossil sources in the model calculations. An electrification of industry processes is not considered here.

Additional assumptions in the other scenarios are the following:

Energy efficiency scenario

- Energy savings and efficiency measures reduce the base current load from 481 TW h to 360 TW h, in accordance with the target of the German government to reduce energy consumption for original power applications by 25% until 2050.
- Energy demand in industry decreases by 0.5% annually.
- Solar thermal energy gains importance for low-temperature heat generation in buildings.
- In the model calculations, no costs are considered for the decrease of the energy demand.

Coal phase-out scenario

- Phase-out of lignite and hard coal power generation until 2040 (elimination of must-run conditions for lignite/coal and oil power plants).

Import scenario

- Expansion of the European electricity network, by doubling the total capacity of German interconnections with neighboring countries until 2050.

The three elements are then connected in a last scenario ("**Active scenario**") to show the effects of combining all efforts on the total system.

C. Modeling of the three key elements

Energy efficiency is given based on the input parameters mentioned below. However, the efficiency measure in the electricity sector and industry sector is not linked with cost. Therefore, the results have to be interpreted by taking cost of efficiency measures into account.

Conventional lignite and coal-fired power plants (as well as oil-fired power plants) are initially recorded with power plant-specific age and installed capacity using the so called "Kraftwerksliste" (list of power plants) for 2015.[31] During the observation period until 2050, the installed capacity of these power plants will be reduced after expiry of the respective technical lifetime. In the model, it is not possible to replace these power plants with new hard-coal, lignite, or oil-fired power plants. Nor is it possible to take them out prematurely. Therefore, they are not the subject of the optimization. Furthermore, lignite and hard coal fired power plants are required to run at least at a certain capacity at all times ("must-run condition"). This constraint is modelled to represent technical issues such as limited ramping potential and heat supply of these power plants.

In the phase-out scenario, it is assumed that after 2030, it is not allowed to construct new power plants using coal or lignite. After 2040, the must run condition of coal power plant is set to zero. Because the emissions of coal and lignite power plants are high compared to other conventional power plants (mainly fueled by gas), this leads to direct phase out of coal power plants under strong CO_2 emission reduction targets.

On the modeling of electricity imports, electricity imports are treated as additional flexible generation capacity from neighboring countries. It comes with a specific cost per MW h but does not contribute to the CO_2 emission budget of Germany. The export of electricity is possible if it can supply any application or demand in Germany. However, it is fully accounted for the German CO_2 budget if it is generated on fossil fuels. In the basis scenario, an interconnection capacity of 15 GW is available in each hour but is positioned in terms of use and cost between combined cycle gas turbine (CCGT) plants and open cycle gas turbine (OCGT) located in Germany. In the import scenario, however, the interconnection capacity is extended to 30 GW and is preferred compared to CCGT and OCGT. The reason for this assumption is that cheap electricity is available in neighboring countries either from solar of wind and also from hydropower or pump storage which can flexibly feed in the German electricity system.

III. QUANTITATIVE RESULTS FOR 2050

The results from the REMod model consist of a solution for structure (technology capacity/number each year) and operation (per hour) of the energy system from today to 2050, which is the target year of the German Energiewende and related climate protection measures. The results of all scenarios are presented for each sector in year 2050 to show the differences in the last year for each scenario.

A. Electricity sector

Electricity becomes the dominant energy carrier in each scenario considered here, as power from wind and solar power plants is the main renewable energy source (RES) available. Consequently, by 2050, the electricity system is based on high shares of renewable energy sources. The installed capacity of renewables, foremost wind power, and solar PV is the main generation capacity, ranging from 350 GW to 500 GW depending on the scenario assumptions (Fig. 2). Flexible power plants such as OCGT or CCGT running with natural gas are the backup technologies with an installed capacity between 66 GW and 120 GW which are operated in the case of low wind speeds or low sun irradiance.

Modifying different key parameters leads to changes in the generation capacities as follows: Higher efficiency measures result mainly in a reduction of flexible power plant capacity, whereas a faster coal phase-out and higher electricity import reduce both the local demand of RES power and the local demand of flexible power as these measures reduce the CO_2 emissions in the German power sector directly. The main driver for the reduction of flexible power plants in the efficiency scenario is the reduction of peaks in the electricity demand. In the other scenarios, lower CO_2 emissions in the electricity sector lead to a lower need for renewables: in the import scenario, more (CO_2 free) electricity can be imported from the neighboring countries. In the coal-phase-out scenario, emission-intensive power plants can be substituted by low-emission flexible plants such as CCGT, leading to lower specific CO_2 emissions in electricity generation. The combination of all three key elements (Active scenario) shows the positive impact of coupling the elements on the demand for renewables; the capacity of renewables is the lowest with 350 GW. Interesting to see also in the active scenario is an increase in flexible power plants. This fact is caused by the combined measures which leave more potential for gas fired power plants to be operated.

A comparison of wind and PV shows that the key elements mainly impact the installment of PV, which is explained by the more equal distribution of wind feed-in over time, whereas a high share of PV generated massive excess energy at noon on many days.

The operated back-up capacities, which run mostly with natural gas, consist of a large fleet of CHP power plants which also feed heat in the existing and newly constructed large heat grids (Fig. 3). Their use (~100 TW h) is also beneficial in the future as the winter peak demand from heat meets very well the electricity generation from these power plants. In the scenarios without active coal phase-out, some generation from lignite and coal still exists in the system but full load hours are low compared to today's value as the CO_2 constraints put high burden on the use of these power plants with high specific CO_2 emissions. Conventional power plants for the absolute peak residual load without any renewable feed-in are CCGT and OCGT from which OCGT is operated with less than 150 operating hours per year in 2050.

In total, electricity generation increases to over 1050 TW h in year 2050 in the basis scenario, due to the increasing electricity demand in the other sectors (mainly heating and transport) and conversion in PtX technologies, producing, e.g., hydrogen. In Fig. 4, the share of RES generation on the total generation is indicated. Compared to today, huge growth in all scenarios compared to 2014 can be found. Also in the scenarios with the separated elements, electricity generation is not decreased compared to the basis scenarios, as shifts to other technologies take place. However, in the active scenario, the coupling of all elements leads to a strong decrease in electricity generation to

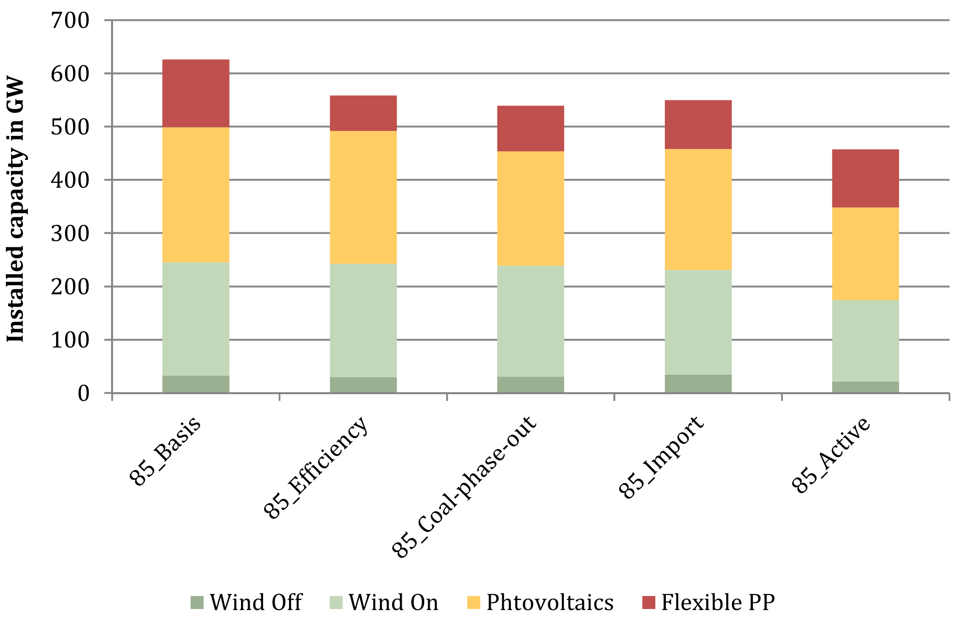

FIG. 2. Installed capacity of power plants in Germany in 2050.

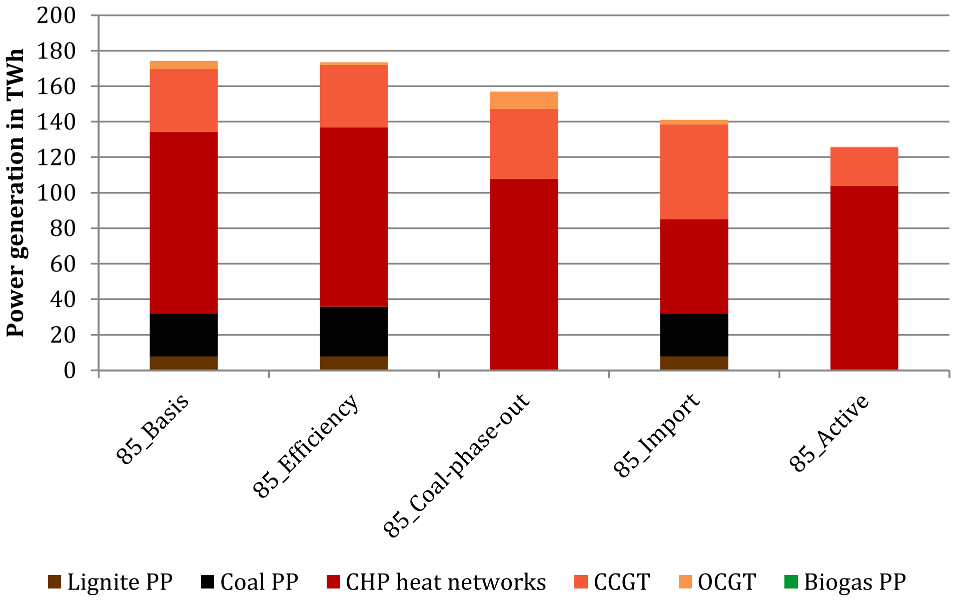

FIG. 3. Electricity generation of flexible power plants in 2050.

750 TW h which is not far away from today in the total number of 550 TW h. In this scenario, all elements lead to an avoidance of a large use of PtX technologies (with their low efficiency in the conversion chain) and a positive effect of the efficiency measures.

Today's conventional generation not based on gas, i.e., lignite, coal, and nuclear, does not have any market role in 2050. Lignite and coal power plants are not used anymore as the high CO_2 emission factor per generated electricity does not provide a basis for operation under a limited CO_2 budget.

All three key elements by themselves thus lead to a direct change in the deployment of renewables as each activity lowers the need for renewables slightly. By carrying out all three elements at the same time in the active scenario, the effects are added and a much lower capacity of installed renewables is needed to come to an optimal solution. Looking at the data, the following influences of each activity can be derived:

- The efficiency measures reduce peaks in the electricity demand. The coal phase-out reduces the need of electricity

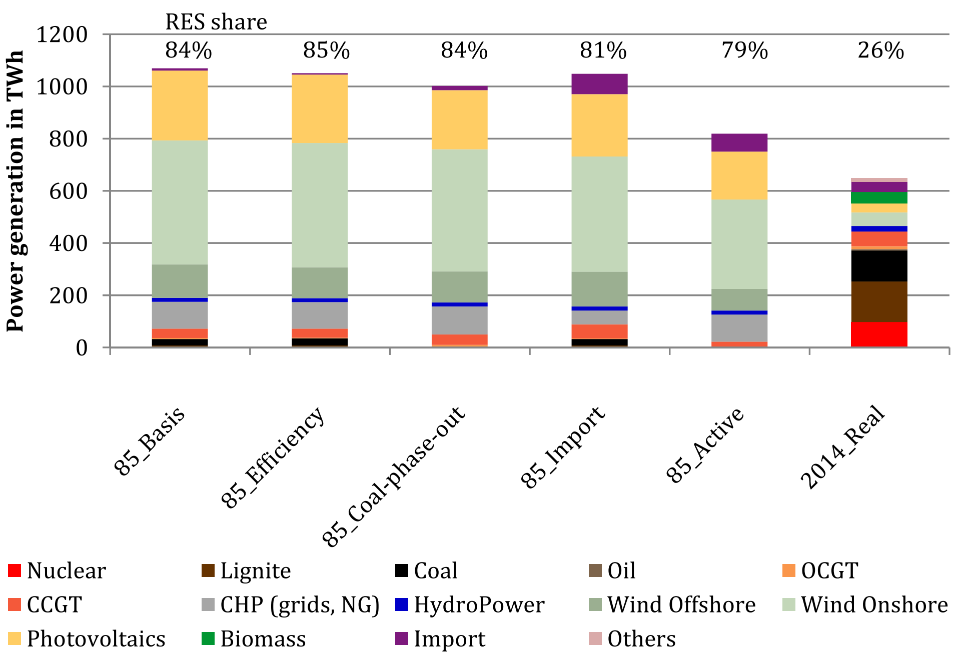

FIG. 4. Electricity generation of all power plants and import/exports in 2050 compared with 2014.

in the other sectors as conventional fuels can be used in heating and transport as less CO_2 emissions are created.

- Electricity imports are not connected to CO_2 emissions in Germany as they have to be accounted for in the country of generation (however, it should be assumed that neighboring countries do also follow a decarbonization strategy as electricity imports from emission-intensive sources would contradict the idea of the Energiewende). Therefore, the imports reduce the need for national electricity generation and consequently national generation from renewables.

It can be concluded that the impact of each activity is predominantly complementary. Fewer installations of renewables reduce the need on new power plants, land use, and also expansion of the electricity grid. In Sec. III B, it can be seen that the need for PtX converters for the production of hydrogen, CH_4-gases, and synthetic liquid fuels is reduced in this scenario as well.

B. Power to gas and power to liquid technologies

Productions of PtG and PtL fuels are a technical option in REMod to decarbonize fuels in the energy system and to provide long-term energy storage. The production of hydrogen, for example, enables us to decouple the direct use of electricity in the transport sector from the electricity generation mainly based on solar and wind. By producing hydrogen, the model has the possibility to store the energy in an energy carrier over some days or weeks. As the model includes the weather situation of the historic years 2011, 2012, and 2013, it is possible to capture many different weather situations, e.g., days with high and low feed-in situations from solar and wind. Typical operation of hydrogen production is found to be coupled to periods with surplus from renewable energy production.

To produce these synthetic energy carriers, electrolysis and methanation [methanation here includes an electrolysis capacity plus Sabatier process] are required. The capacity varies in each scenario between 20 and 30 GW (see Fig. 5). In the Basis scenario, the largest amount of converters is installed as here the demand for renewable energy is the highest. As these converters and also the required renewable energy are expensive, the three key elements in the active scenario strongly reduce the need to produce these synthetic energy carriers as electricity imports, energy efficiency measures, and the coal phase out positively influence the system. However, synthetic fuels produced from renewable electricity sources are an important part of the solution in every constellation.

C. Heating sector

Today, oil and gas boilers and heating networks are used the most often to provide space heat and warm water. However, by 2050, a shift to electric heat pumps (HP) and more heating networks (heat generated from CHP and HP) is suggested by the results to reduce CO_2 emissions (Fig. 6). All in all, the share of electrical driven heating systems drastically increases in all scenarios (between 50% and 70% by 2050), leading to an increasing electricity demand in the heating sector.

The import scenario shows an interesting result: here, the electricity import leads to an even higher share of electric HP than in the other scenarios. However, in the active scenario, this result is balanced by the effect that all the other measures (such as demand reduction in the electricity sector) lead to a more equal use of technologies (including a higher share of gas boilers is possible).

It is important to note that the high peak electricity demand of heat pumps can be mitigated by making use of decentralized and centralized heat storages. They are used by the model in all scenarios. The high electricity demand by HP, however, is part of the reason why the back-up capacity of

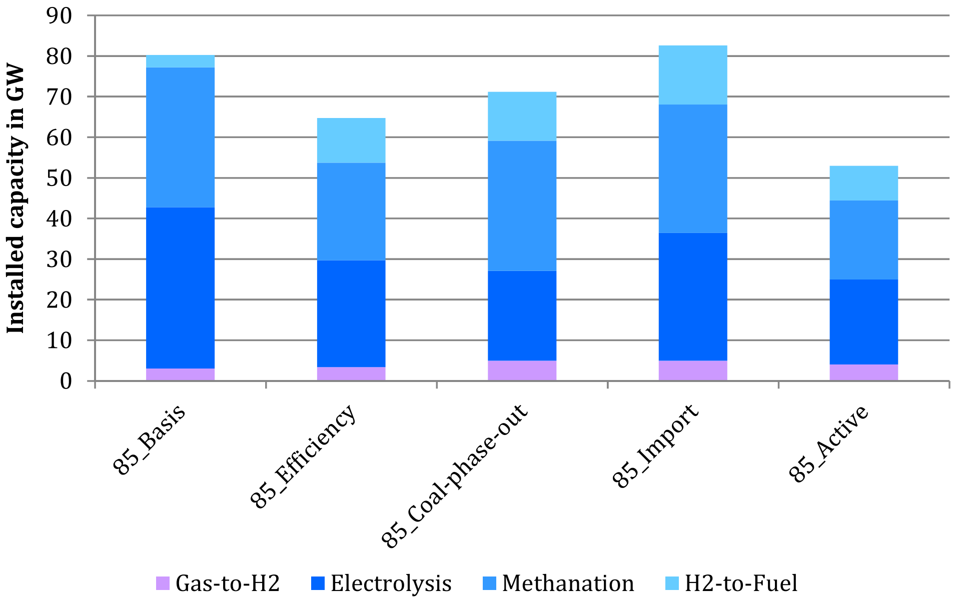

FIG. 5. Installed capacities of converters for synthetic gases and liquids in 2050.

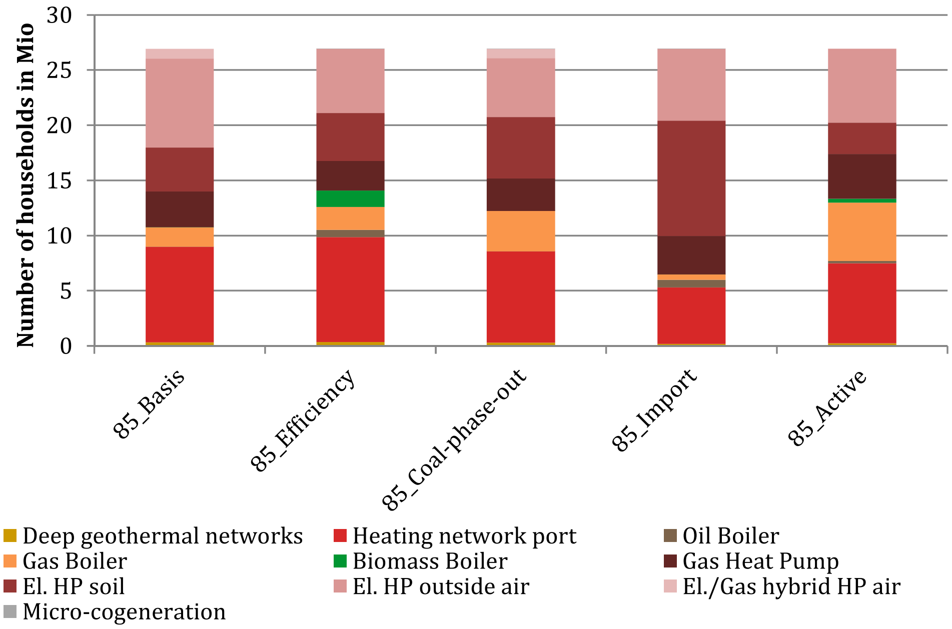

FIG. 6. Distribution of heating technologies in the heating sector (private households) in 2050.

conventional power plants is still quite high in 2050 due to the constraint of security of (heat) supply during each hour of the year.

The level of refurbishment is directly linked to technologies providing heat. As REMod endogenously optimizes the level of refurbishment in the building sector (and consequently the heat demand), each scenario can be evaluated regarding this effect (see Fig. 7). The basis scenario has renovated over 90% of the buildings, including 15% of buildings at a very high efficiency standard. In the active scenario, the need for refurbishment measures is reduced by the reduction of CO_2 emission in the electricity system and due to a lower energy demand. The model does not chose the expensive option "Refurbishment" and is able to supply the non-renovated buildings with energy with low CO_2 emissions as the key elements provide the option to lower this effort.

In the basis scenario and in the import scenario (due to the good availability of import electricity), the degree of electrification in the heating sector is high (see Fig. 8). It continuously increases to almost 70%. Also in the Coal phase-out scenario and efficiency scenario, the degree sill accounts for 60%. Only in the active scenario, all the elements lead to a lower share of under 50% created by electric heat pumps, deep geothermic, and heat rods. Interesting to see is that already by 2020, a huge

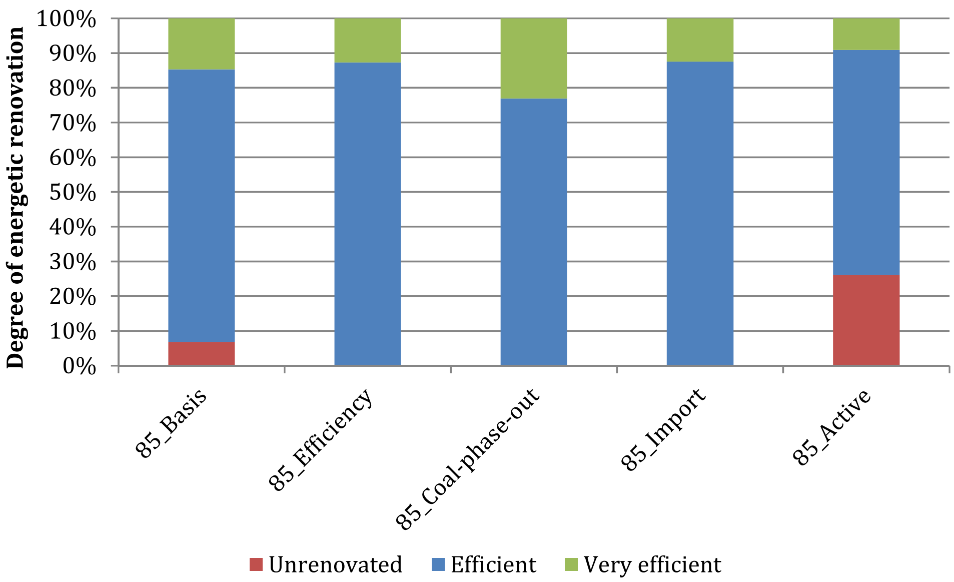

FIG. 7. Level of refurbishment of buildings in 2050.

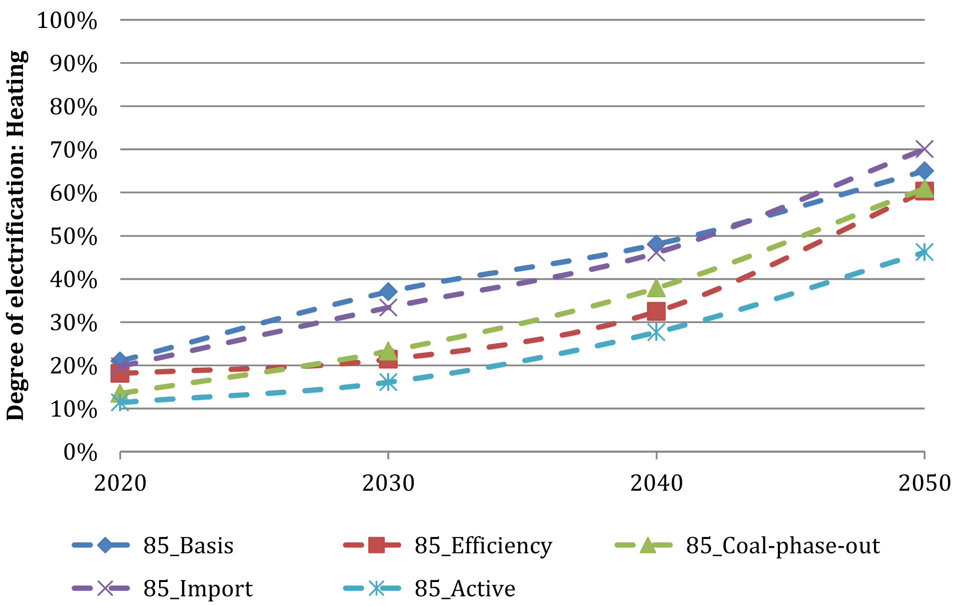

FIG. 8. Degree of electrification in the heating sector.

difference exists. This is based on the reason that the model proposes some electrification activities by 2020 due to the electricity demand reduction in the two scenarios activity and efficiency.

D. Transport sector

Currently, automotive companies are developing and offering new car concepts in addition to the conventional internal combustion engines (ICEs) which normally run with diesel and gasoline. Hybridization with an electric motor and small battery has been available on the markets already for over 20 years (mainly starting with Toyotas Prius on a large scale). Nowadays, pure electric vehicles with large batteries for ranges of 200 to 300 km start to enter the market. However, also vehicles using hydrogen and fuel cells are another potential option. All of these options are tested in REMod by including development paths for the performance and cost of these vehicle concepts.

The optimization results show in all scenarios high shares of pure electric vehicles up 90%, for passenger cars and for trucks (Fig. 9). However, it has to be noticed that restrictions for end-users, for example, considering charging and driving ranges have been assumed to be solved for pure electric vehicles. Furthermore, the category "trucks" include not only large trucks with 40 ton weight but also delivery trucks. Most of these "smaller" trucks are used with lower driving ranges and with regularly charging options during their daily use. The high share of electric trucks is expected to use also electric overhead lines for long distance transport.

In the basis scenario, the highest share of electric vehicles is selected as the direct use of electricity is the most effective one. However, if efficiency measures, coal phase-out, or imports are more prioritized, either ICE vehicles or hydrogen vehicles are used more often in the transportation sector. The main reason why hydrogen is used is that it enables the system to make

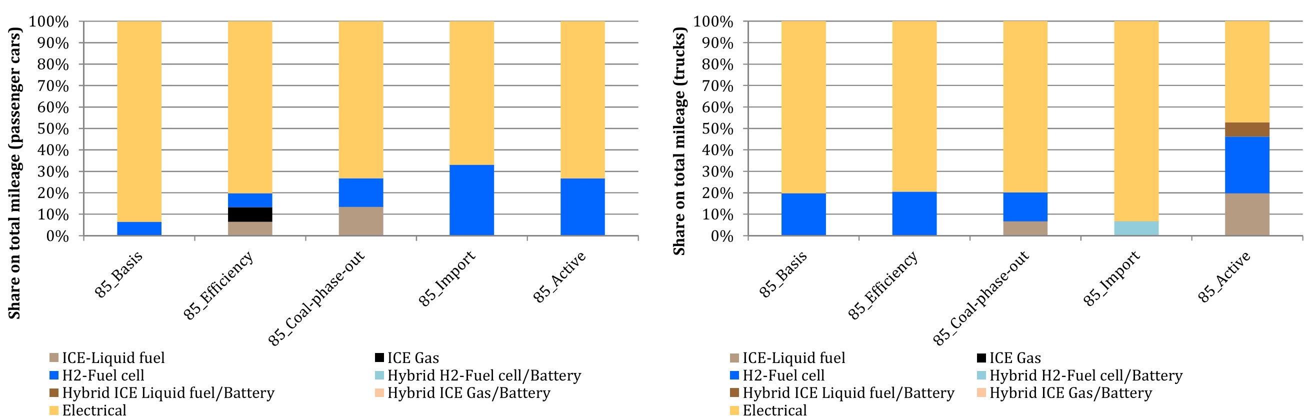

FIG. 9. Distribution of vehicle concepts on total mileage in 2050 (left: passenger cars and right: trucks).

use of the surplus electricity from RES during many hours of the year to produce hydrogen time. This energy can be stored and then be used at any given time in the transportation sector. In the active scenario, the lower CO_2 emissions in other areas provide the opportunity to also use some share of conventional fuels in addition to hydrogen in 2050. Figure 10 shows the degree of electrification in different scenarios. It varies strongly especially for trucks. Again, the key elements provide the opportunity to be more flexible in the vehicle concepts by using different options in addition to pure electric vehicles.

E. Industry sector

For the industry sector, the results show a high use of natural gas and in addition some biomass (biogas), both of which are used to supply processes with high temperature heat. A trend of the direct electric heater (and heat pumps) can also be expected in the future. Further results on the industry sector are beyond the scope of this paper and are not discussed here. Currently, this sector is being detailed to be able to consider additional technology options for the supply of process heat, including heat pumps, boilers, fuel cells operated with hydrogen, electric heaters, and others.

F. System cost of the energy transition

By 2050, the energy transition to a low carbon emission system comes with massive investments in new infrastructure and products. One main reason is that there will be a shift from conventional technologies to many different technologies. The REMod model calculates the cost for new investments and for the operation of each application in the energy system. For example, the cost for vehicles, heating systems, or power generation technologies is included and also electric grids are implemented as additional cost per installed RES capacity.

Each key element leads to a direct cost reduction compared to the basis scenario of around 500 billion EUR (around 8%). However, the total costs cannot be compared directly: efficiency measures and the coal phase-out are not linked with additional cost in the model calculations. Therefore, a budget of about 500 billion EUR (or around 16 billion EUR per year) can be estimated for each activity to be valuable for the system. Furthermore, electricity imports are included with a specific price of 60 EUR/MW h but are not linked with CO_2 emissions for the budget of Germany. If Germany would have to compensate financially for the CO_2 emission in neighboring countries, additional cost would have to be included into consideration. The active scenario is significantly cheaper than the other scenarios. It adds all cost benefits from the separated elements to a final sum of 4700 billion EUR from today to 2050—roughly 1500 billion EUR less than the basis scenario.

In all scenarios, investments account for the largest share of the systemic costs, as the energy system changes from a fuel based energy system to a renewable energy technology, converter, and application based energy system.

IV. RESULTS ON THE CHRONOLOGICAL DEVELOPMENTS IN THE ACTIVE SCENARIO

The analysis has shown that the active scenario offers many advantages from a technological and economic perspective. Combining elements in the fields of energy efficiency, coal phase out, and electricity imports significantly reduces the necessary expansion of renewables and the degree of sector coupling needed for a successful energy transition. This can help us to lower the systemic costs of the Energiewende and also foster the acceptance of all involved parties. However, these elements will require concerted policy efforts and support measures in order to be implemented. Of course, a coal phase-out can also add high cost for compensation, and energy efficiency normally requires expenditures for the measures of energy efficiency itself.

In the following figures (see Figs. 11 and 12), the potential temporal development of key technologies based on the model results for an optimal transformation path is displayed. Renewables (mainly PV and wind power) continue to grow until 2050, whereas conventional flexible power plants, gas turbines, and CHP plant fueled by natural gas remain stable at 95 GW. Between 2030 and 2035, already 200 GW of renewables are required to reduce the energy related CO_2 emissions by about 50%.

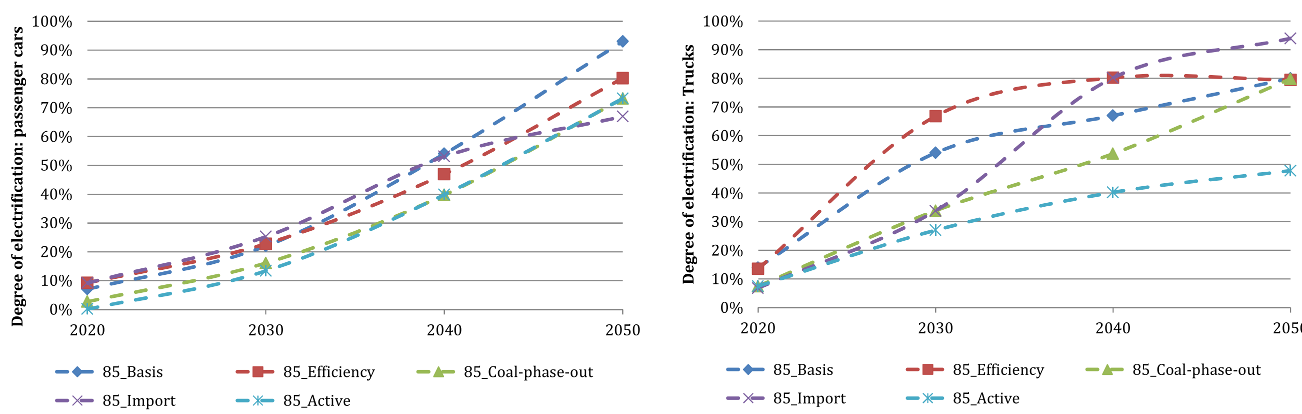

FIG. 10. Degree of electrification in the transport sector (left: passenger cars and right: trucks).

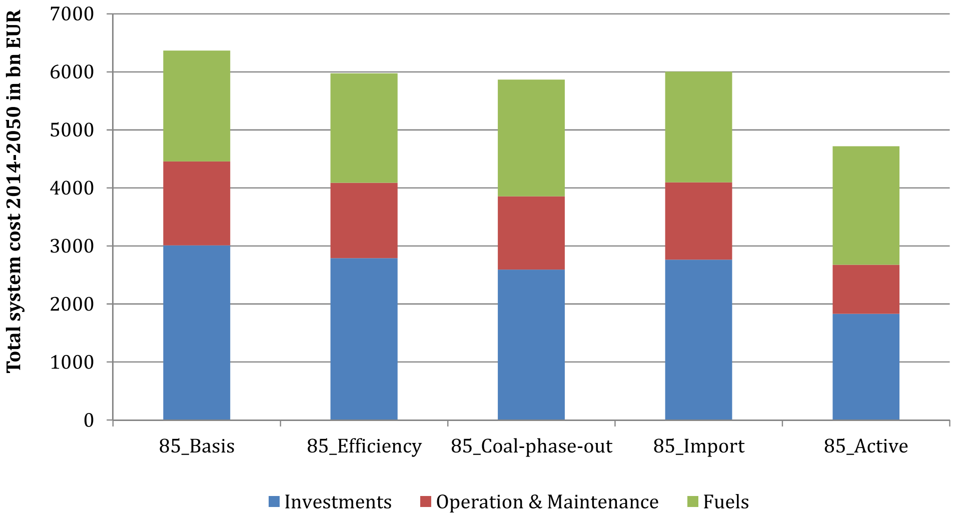

FIG. 11. Cumulative total system cost from 2014 to 2050 in billion EUR.

Electric vehicles and heat pumps are the first important drivers of this additional electricity demand. Already in 2035, the number of electric vehicles reaches almost 15 Mio cars in the active scenario. By 2050, almost 90% or 32 Mio cars are equipped with electric motors and a battery. The number of heat pumps grows at the same time to about 12 Mio applications in the German residential building sector.

Compared to the basis scenario, lower P2G and P2L installations (electrolysis, methanation, and Power2Fuel) are necessary for the same reduction of CO_2 emissions. However, after year 2040, the capacity for electrolysis still increases to over 20 GW. Additionally, installation for the production of synthetic natural gas (methanation) also grows to almost 20 GW of installed electric capacity for the electrolysis. Due to lower efficiency and higher cost, P2L (Power2Fuel) only adds about 9 GW by year 2050. This clearly shows that the importance of renewables and of new technologies, such as electric vehicles cars and P2G/P2L conversion, will continue to grow in the future. The key elements, i.e., energy efficiency, a coal phase out, and high electricity imports, can reduce the needs for these technologies and applications to a certain degree.

V. DISCUSSION AND CONCLUSIONS

Energy transformation from carbon technologies to carbon free technologies such as renewables requires huge efforts in terms of investments and also changes in behavior and thinking to introduce all new and ground-breaking technologies and applications. Sector coupling and the interactions of many new technologies such as heating technologies or automotive technologies with the power system will especially increase the use of electricity. However, key elements (="facilitators of the transformation") such as coal phase-out, energy efficiency, and electricity imports can lower the effort and burden which come along with the transformation. This paper focuses on providing quantitative and qualitative results on the questions of fostering these elements in an energy strategy. In a case study, this question applies to Germany.

This paper presents a review of existing methods and models to assess today's and future energy systems with their new characteristics of representing technologies and features such as renewables and sector coupling. Under these models, the energy model REMod provides an innovative and advanced approach as it includes a high temporal resolution (hourly) and an implementation of all sectors (power, heating, industry, and transport). Furthermore, it determines an integrated solution of all sectors by direct coupling of all sectors. With these features, it is well prepared to answer the questions on the effects of coal phase-out, energy efficiency, and electricity imports as they influence all sectors if an overall greenhouse gas emission target should be reached (by 2050).

With the implementation of each of the three elements, efforts (and costs) can be reduced in the energy sector. While the greenhouse gas target of −85% by 2050 compared to 1990 requires a massive investment in renewable energy technologies such as photovoltaics and wind power, each element can reduce the amount of installation (in terms of capacity). By the joint implementation (=active scenarios), the amount of required capacity is reduced by almost 26%. Coal phase-out reduces directly and rapidly the CO_2 emissions per generated kW h in the electricity mix as renewables, and also other technologies such as gas power plants have no or lower specific CO_2 emissions. Energy efficiency reduces demand and consequently the need for renewables and other technologies for energy supply. Imports reduce the need for electricity generation in Germany as it uses sources in neighboring countries. Clearly, it is important to define what kind of source is responsible for these imports as it impacts the European energy and emission targets. However, Germany can also profit from sources in other countries which have high potentials for renewables in terms of land resources or weather conditions.

Due to these general consequences of the three elements, the impact is indirectly fed into the other sectors. As the energy systems would require some long-term flexibility (over some weeks), the optimal solution in the basis scenario includes large

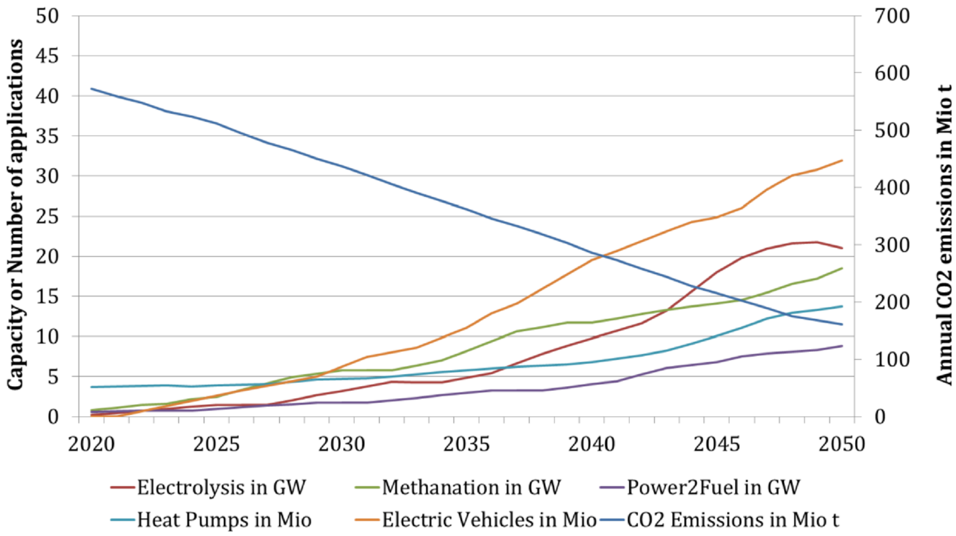

FIG. 12. Temporal development of key technologies in comparison to CO_2 emission reduction (above: power generation technologies and bottom: key sector coupling technologies).

investments for hydrogen generation with electrolysis to produce a flexible, green energy carrier. However, the expansion can be highly reduced by energy efficiency and to some extend with coal phase-out. In the heating sector, additional efforts can reduce the dependence on direct electricity use by being able to use a larger mix. Also in the transport sector, the same phenomenon is found as the three elements together leave more space for conventional engines to be operated with fuels (see Active scenario) instead of a high degree of electrification in the basis scenario.

Nevertheless, the implementation of the three elements requires also expenditures over the next 30 years. As the cost of each element is still uncertain, the analysis in this paper is limited to the point that it provides overall numbers for the potential cost reduction which are created by their implementation. However, this paper is not able to calculate the cost for it. As the cost reduction per element is projected with the model at around 16 billion EUR per year, further research has to be carried out if these savings are large enough to pay for their implementation. The amount seems quite high for electricity imports as the model includes the cost for imported energy. However, the social cost of new transmission lines could stand against this element. In the case of coal phase-out, two main issues should be considered. First, the coal phase-out will bring changes to the regions and citizens who host these power plants and will be affected by their phase-out. Second, energy security in terms of fuel imports (see Refs. 32–35) and the grid impact have to be assessed carefully. Measures for energy efficiency in buildings are linked with other developments in the building sector and with the role of the investor and owner. Therefore, decision frameworks are structured very heterogeneously (see Refs. 36–39).

This paper concludes with a final analysis of the chronological development of power technologies and sector coupling technologies in the active scenario. Such a scenario reduces the efforts, but still the growth of new technologies is high over the next 30 years in Germany. Renewables will continuously grow to over 350 GW in this scenario in which the key elements are realized in time. This means that the coal phase-out is realized around 2030/2035. At the same time, sector coupling technologies (heat pumps or electric transport) and energy efficiency will largely implemented. In 2050, electrolysis with a capacity of 40 GW is proposed (21 GW hydrogen production only and 19 GW for further use in methanation processes). The setting of renewable deployment on the agenda was quite successful during the start of the Energiewende over the last 8 years. However, the further paths of the energy transformation include some more key elements in the energy and climate strategy; three of them have been assessed here in this paper.

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