1. Introduction

During the last decades the complexity of energy system modelling increased significantly. While most of the scenario studies at the beginning of the 90's have focused on the feasibility of high proportions of renewable energy sources (RES) in the electricity system on a national scale (see e.g. the analysis of the German energy system in [1]), current scenarios are often based on deep sectoral coupling with high technological detail and linkage of several sophisticated models to derive further insights into specific relevant aspects (e.g. grid constraints, storage demand or environmental implications). Using these complex approaches, scenarios provide important insights into techno-economic, societal and political options for energy system transformation and their various impacts. Therefore, they are often used to guide and influence decision makers and to motivate or justify policy interventions and developments. Energy scenarios have received a strong response in the media, in public and also in politics [2–4]. The great influence of decision making on society requires comprehensive, transparent, and robust results and conclusions. Ideally, this information originates from scenario studies that investigate a broad range of possible conditions and available options. Such studies need to have a holistic view and integrate substantial state-of-the-art background knowledge e.g. about current policies, sectoral and technological development, potentials and constraints of future market developments or ecologic and economic effects of certain pathways [5]. Furthermore, accurate and reliable energy data are always necessary for effective decision making.

In the scientific, political and industrial context, resulting scenario data is used as an orientation framework or even for model parameterization in further scientific analyses, e.g. of economic, ecologic or societal drivers and impacts. Advanced energy system modelling approaches consider a multitude of interrelations between energy demand and supply options and involve a variety of assumptions to represent them in the models. Therefore, model based scenario building often leads to results that are not fully transparent and understandable for scientists, stakeholders and other addressees. Sometimes this lack of transparency gives rise to the assumption of a deliberate manipulation of the view of the future of energy supply. For example, scientists frequently find traces of a systematic bias, such as the conservative predilection by the World Energy Outlook (WEO) of the International Energy Agency (IEA), whereby the role for fossil fuels is substantiated, and dynamics involving progress for RES is repressed, which seems to be consistent with the interests of IEA's member countries [6], [26].

In addition, the use of complex models or even model coupling is associated with a large number of uncertain and influencing assumptions for their parametrization, so that their overall quality and consistency appear to be unclear [7] [32] [33]. To grasp the complexity of models with regard to the applicability of various modeling techniques, Börjeson et al. [8], [9] present classifications of energy system models (ESMs) and scenarios clustering according to aspects such as planning tasks (e.g. international or national policy advice, sector-specific analyses) and model types (e.g. top-down and bottom-up models). However, Sullivan et al. [10], [11] emphasize that, despite a classification of models, a complete understanding of scenario analysis and its results can only be achieved through the greatest possible transparency and comprehensibility of applied data and models. One recent work by Cao et al. [27] provides a fully operational transparency checklist for modelers with the focus on scenario studies that examine energy systems. Hülk et al. [12] already applied this transparency checklist methodology to evaluate the degree of transparency in their own modelling work. They and many others (such as [34] and [36]) derive the idea of an open source and open data community from the political desire for more public transparency and comprehensibility of scenario studies. The systematic literature review and qualitative evaluation by Wiese et al. [28] revealed, that also for open energy modelling frameworks the main challenges are complexity, scientific standards, utilization, interdisciplinary modelling, and uncertainty. A high scientific standard of the models as tools for scenario building does not guarantee that robust statements are made in studies. Rather, the approaches must be evaluated comprehensively, from the narratives and assumptions, the data sources and model approaches to the data evaluations and the derivation of conclusions. The extent to which scenario analyses can be evaluated on the basis of published scenario studies is the subject of this article.

In the following analysis we consider three recent scenario studies resulting from concrete applications of ESMs. A systematic and comparative review provides a condensed characterization of the studies and the modelling framework behind them and reveals their level of transparency and comprehensibility. This article has the following structure: in Chapter 2 we describe our methods, and in Chapter 3 we show and discuss our comparison results. Chapter 4 presents our further implications and recommendations for scenario developers before we present our final conclusions in Chapter 5.

2. Methodology and concept

We focus our analysis on the Climate Protection Scenario 2050 (CPS) [24] for Germany, the European Union (EU) Reference Scenario (ERS) [13] for Europe and the WEO [22]. All three scenario studies are model-based and represent important and current quantitative bases for advising energy politics as well as for investment decisions in businesses and discussions in the society. Each scenario is conducted at a different regional level: the CPS for the energy transition in Germany at the national, the ERS for the energy future in Europe at the supranational level, and the WEO for long-term scenarios according to different world regions at a global scale. We outline their differences with a special focus on traceability of model approaches and model linkages, the ability to understand and access input and output data. We use only public available information such as the main study and study-related supplementary documents since we demand that study authors present the data and models in a form that is comprehensible to the reader within the study itself (see Table 1 for used documents). Therefore, analysis of cited secondary literature (peer-reviewed papers as well as grey literature) is beyond the scope of this study.

Table 1: Sources included in this assessment

Scenario study	Information gathered	Source	Comments
ERS '16	Main study	[14]	The main study report only provides results in the main text and supplementary result sheets, and there are study specific supplementary model documents available online. However, additional efforts are needed to interpret model input and output, model linkages related to supported scenario analysis.
	Supplementary on the energy system	[15]	
	Supplementary on transport	[16]	
	Supplementary on biomass	[17]	
	Supplementary on air pollution and climate change simulation tool	[18]	
	Supplementary on computable general equilibrium model used for value added projections by branch of activity	[19]	
	Supplementary on global forest model	[20]	
	Supplementary on agricultural activity projections	[21]	
IEA WEO '16	Main study	[22]	The main study includes objective and results, while the supplementary information contains the description of the model and data sources.
	Supplementary on methodological description	[23]	
CPS '15	Main study	[24]	The main study provides results and background information about the models and the model linkages. There are no further study-specific supplements.

Our analysis contains the following main methodological steps:

1. We define a suitable list of categories and indicators for the study evaluation based on literature and own consideration from modeler and user perspectives.
2. We gather and describe relevant data for the three selected scenario studies in a systematic and comparative way.
3. We identify the main differences of the scenarios with regard to defined transparency indicators.
4. We evaluate how far the applied models and further assumptions for scenario analysis are traceable, input and output data are understandable and reliable, and relevant information is accessible.

Table 2 shows the selection of the categories used as evaluation criteria, which is mainly based on [27]. The main categories are basic information on the study ('Scope & purpose of analysis'), specification of data used and generated ('Quantitative assumptions & results'), information on the analytical approach ('Applied methods & models'), and other issues such as implicit assumptions and inconsistencies ('Further aspects'). We partly modify the evaluation criteria and adjust them to our purpose to understand and compare the scenario building in the studies. While Cao et al. [27] take the perspective of the modeler and formulate a systematic manual for transparent documentation, we are also looking for information that allows the greatest possible understanding of the work carried out, the data used and the results obtained. Hence, in addition to the check list from Cao et al. [27] we use the model classification method from Van Beeck et al. [25] and own considerations in order to define a list of categories that is well suited for looking at the studies from an external perspective. This first step in our analysis was also necessary to adapt the categories to the information available from scenario reports and documentations.

Table 2: List of the categories analyzed for each of the three studies

Category	Analysis points, collected for each study
Scope & purpose of analysis	Indication of authors and institutions
	Aim and funding of the study
	Indication of geographical scope
	Indication of time horizon
	Scenario names and aims (normative/explorative?)
	Storyline behind the scenarios
	Assumptions about socio-economic development
Quantitative assumptions & results	Main empirical data sources used (e.g. economic data, price data)
	Data requirements (e.g. level of aggregation on demand side, temporal resolution, spatial resolution)
	Input and output data access
Applied methods & models	Applied models and purpose (e.g. forecast or impact analysis of policies)
	Model structure (internal and external assumptions in the model)
	Analytical approach and methodology (e.g. top-down/bottom-up) (e.g. optimization, simulation, accounting, economic equilibrium, game-theoretic, or agent-based)
	How can these models consider the future energy system (decentral, flexible, new technologies)?
	Technological resolution on supply side
	Model validation
	Uncertainty treatment in the model and reporting
	Model documentation
Further aspects	Neglected relevant aspects and significant implicit assumptions
	Other relevant exogenous assumptions
	Inconsistencies in the approach
	Inconsistencies of input data
	'Speculative' assumptions
	Are the results published conveniently?
	How are results considered by public / academia?

Detailed results of the systematic and comparative analysis for all three studies are provided in the annex. The comparison is presented in a structured table including a description of the data structures, the analytical approach, methods used as well as comments on how the studies cope with our evaluation criteria. Main aspects according to the four evaluation categories are further discussed in Chapter 3. In addition, we create a concise graphical overview (**Fehler! Verweisquelle konnte nicht gefunden werden.**) that shows the typical structure of scenario analyses with the sectors and components analyzed and the underlying model types and assumptions.

3. Scenario characterization and discussion

In this section we discuss results of the evaluation of all three studies according to criteria defined in Table 2 (for further details regarding the results, see Table A 1 in the annex). In the following, we will discuss the most important aspects for which we have gained interesting insights.

3.1 Scope and purpose of analysis

As indicated in Table 2 the category "scope and purpose of analysis" is measured by seven evaluation criteria. In the three studies, background information on authors, participating institutions, aims and funding of the studies, geographical scope, time horizons, etc. are described in a comprehensible way. The German as well as the European study were each funded by the state institutions Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMUB for "Bundesministerium für Umwelt, Naturschutz und Nukleare Sicherheit") and the European Commission (EC), respectively, while the IEA and the member states in the agency (OECD states) are not assigned to any political institution. The aims of the studies are very similar in principle and are clearly defined: to inform policy makers where current policies and policy ambitions may lead the energy sector as well as which policies and action measures are needed to achieve specific climate targets. Naturally, the WEO addresses the global objectives of controlling global warming (in the case of below 2°C above pre-industrial levels), while the reports for the BMUB and the EC deal with country- or EU-specific climate targets. The WEO also claims to be carrying out a first comprehensive study of the new era launched by the Paris Agreement. The time horizon for the German study is until 2050, while the WEO analyzes the transformation paths until 2040. Of the seven scenarios in the ERS, only the reference scenario (REF) has a perspective until 2050, while all other six policy scenarios have a horizon only up to 2030. This makes it difficult to allow for a comprehensive assessment of different long-term measures and impacts of possible strategies in line with specific global objectives (such as the 2°C target). The CPS and the WEO explicitly examine explorative scenarios, whereby the Existing Measures Scenario (EMS) scenario for Germany corresponds to the current policies scenario (CP) for the worldwide analysis. For both scenarios it is assumed that the current legislation will be continued and that no new legislative proposals or efforts will enter into force or be implemented. In the New Policies Scenario (NP) of the WEO, the implementation of the political announcements and plans up to 2040 is assumed (current goals, targets and intentions, such as available nationally determined contributions for the Paris Agreement). The WEO also analyses a normative scenario in which the 2°C target would be met. The normative goal of avoiding global climate change is implemented in the CPS and ERS in two (CS 80, CS 95) and six scenarios (EUCO27, EUCO30, EUCO+33, EUCO+35, EUCO+40, EUCO3030) respectively, using greenhouse gas reduction targets, efficiency measures and share of RES in gross final energy consumption or other specific targets for RES deployment in power, heat and transport sectors. The main quantitative drivers, their differences and the composition of the primary energy demand as well as the CO_2 intensity per Gross Domestic Product (GDP) in the different studies are described in the next section.

3.2 Quantitative assumptions and results

In this section, we focus on main quantifiable assumptions and characteristics of the three studies, such as economic and population trends, energy demand, differences in electricity generation, i.e. shares of RES, fossil fuels, nuclear power and biomass, technological development, and fuel and CO_2 prices. Overlapping geographical analysis frameworks in the studies allow for a comparison of the CPS and the ERS for Germany and the ERS and the WEO for the EU28. Assumptions and/or modelling results on population development and economic growth, coupled with assumptions and/or modelling results on efficiency improvements, generally represent the main drivers of demand development in scenario analysis and may have a great influence on the supply structure and potential depth of sector coupling. Information on the methods and quality of data processing is usually not provided in the studies.

3.2.1 GDP and population development

All studies assume the same population development and GDP growth for their reference and transformation scenarios. For Germany, the CPS and the ERS expect GDP growth of 50.5% (CPS) and 61.5% (ERS), respectively, with population expectations of -10.0% and -9.3% from 2015 to 2050. The ERS and the WEO expect GDP growth for the EU28 to increase by 65.4% (ERS) and 71.2% (WEO) between 2015 and 2040. The population of the EU28 is assumed to grow slightly by 2.5% (ERS) and 0.6% (WEO) from 2015 to 2040. The WEO estimates global expectations for GDP and population growth between 2015 and 2040 at about 150% and around 25%, respectively. The main reasons for the high global GDP growth compared to the EU28 are the assumed strong developments in Asia, the Middle East and Africa. The latter two countries also have the highest population growth rates. The analysis and comparison of the key quantitative assumptions and drivers (GDP and population) for scenario analysis suggests that no disruptive assumptions were made and that differences between the studies are small.

3.2.2 Primary energy demand and CO_2 intensity per GDP

Limited by the analysis horizon of the ERS scenarios, we compare the structure of primary energy supply in 2030, which indicates the mid-term transformation perspectives by different scenarios. For each overlapping geographical area, we present the reference scenario and the most ambitious scenarios in terms of emission reduction and additionally compare the values with the 2015 statistics (see Fig. 1).

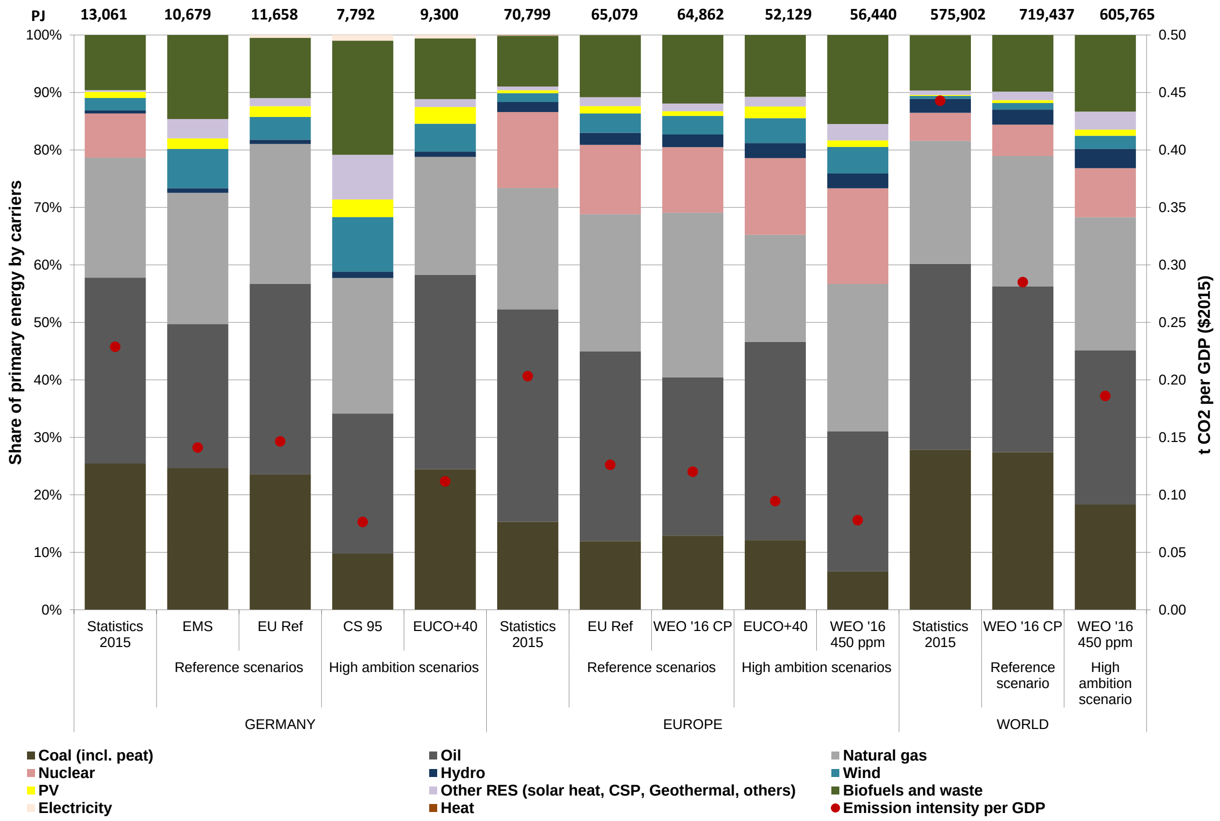


Fig. 1. Primary energy demand by energy type and energy related CO_2 intensity in the reviewed energy scenario studies for the year 2030, differentiated by baseline scenarios and most ambitious scenarios for Germany, Europe and the World. For the ERS and the CPS, the category "Solar" in the datasheets of power generation is assumed to be photovoltaic (PV) only due to the lack of information.

The comparison shows that the studies differ significantly with regard to their primary energy supply structures both in the reference scenarios and in the most ambitious scenarios. The ERS REF and all scenarios for Germany derived in the European study do not take into account the target of the German Energy Concept 2010/2011 (Renewable Energy Sources Act (EEG)) to achieve a share of renewable energies in the total primary energy demand of 30% by 2030 and 60% by 2050. In the Existing Measures Scenario (EMS) and the most ambitious scenario (CS 95) of the CPS, Germany would reach a share of 27% and 41% respectively of renewable energies for primary energy supply, while in the most ambitious scenario (EUCO+40) in the ERS the share would only be 21%. In addition, fluctuating RES (wind and PV) play a much greater role in the CPS (e.g. 12% in the CS 95) compared to the ERS (e.g. 8% in the EUCO+40). For Europe, the shares of renewable energies in primary energy supply do not differ largely from each other in the reference scenarios of the ERS and the WEO, with about 20% and the same shares of wind and PV. Differences can mainly be seen in the role of the fossil energy sources gas and oil, with oil playing a dominant role in the ERS (33%) and gas a dominant role in the WEO (29%). However, in the most ambitious scenarios from the ERS and the WEO, the shares of RES differ substantially with 21% and 27% respectively. The higher ambitions in the 450 ppm scenario in the WEO are reached by large shares of nuclear (17%), and biofuels and waste (15%), while fluctuating RES play only minor role in both studies (5%). Here, too, natural gas dominates the fossil energy supply in the WEO (26%) and oil in the ERS (34%). Since the ERS scenarios are essentially characterized by efficiency increases on the demand side and less by high CO_2 reduction rates (see Section 3.1), RES penetration by 2030 is the lowest in both geographical regions compared to the scenarios of the CPS and the WEO. For example, this results in CO_2 emission intensities per GDP in the EUCO+40 scenario of 1.5 times the CS 95 scenario for Germany and 1.2 times the WEO 450 ppm scenario for Europe. If one compares the energy supply structures in 2015 for Germany, Europe and the world, the shares of fossil fuels do not vary greatly with 79%, 73% and 82% respectively. However, the global CO_2 emission intensity per GDP is about twice as high as in Germany and Europe. According to the WEO 450 ppm scenario, 68% of the world's primary energy supply would still be covered by fossil fuels by 2030, with oil and gas accounting for the highest share at 27% and 23% respectively.

3.2.3 Key differences in electricity generation

The three studies differ in terms of future electricity demand due to various efficiency targets and electrification rates in heat and transport sectors. In the CPS scenarios, the electricity demand decreases until 2030 due to high efficiency targets but increases again due to high penetration of e-mobility, hydrogen demand in transport and methane in power generation (from 2040 on in the CS 95 scenario). This results in increasing rates of demand from 2015 to 2050 of 13% (EMS), 7% (CS 80) and 11% (CS 95). This may be the reason for the significantly lower or even negative growth rates in electricity demand of -6% to 10% for the EU28 and -8% to 7% for Germany in the EUCO policy scenarios. In the WEO, the assumed global energy demand increases by 79% (CP), 65% (NP) and 47% (450 ppm) between 2015 and 2040, while the growth rates for the EU28 are only 23% (CP), 11% (NP) and 8% (450 ppm), respectively. The CPS has a target of a share of RES in gross electricity consumption of 50% in 2030 while in share reaches 44% by 2030 and 60% by 2050 in the ERS REF. For 2050, this is much lower than the minimum of 80% by 2050 in the CPS study. Only the EUCO+40 and the EUCO3030 scenarios for Germany are in line with the 50% target set by the German Energy Concept. The EUCO+40 and EUCO3030 scenarios for Europe also have 2% to 5% higher targets for the share of RES for power supply than all the WEO scenarios (e.g. 50% for the WEO 450 ppm scenario) by 2030. The short-term target by 2020 for the share of RES in power generation in the ERS study for Europe is much higher (36%) than in all the scenarios from the WEO (25%-27%). This means that the ERS assumes a much faster transition for the uptake of RES in power generation in the mid-term compared to the WEO. In the CPS, carbon capture and sequestration (CCS) would only be used in the CS 95 in industry and biomass combustion from 2030 on. The capture rate is assumed to be well below 50 Mt CO_2/yr in all scenario years of the CS 95. In the ERS, fossil fuel combustion with CCS would be implemented from 2020 in the EU28 as a whole but not for Germany. The share of CCS in installed capacity of fossil fuel power plants would reach up to 5% by 2050 for the EU28.

Nuclear would phase out for Germany from 2025, while the share of nuclear in installed power capacity would reach 7% by 2050 in the EU28. In the WEO, a renaissance of nuclear energy takes place in all scenarios with shares of 9% (CP), 12% (NP) and 18% (450 ppm) in global power generation. In the 450 ppm scenario, CCS would play a greater role from 2025, since 4% of global power plants are equipped with CCS and 60% of them are coal-fired. In the 450 ppm scenario in 2040, the share of coal power plants would only account for 7% of total installed capacity while by then 70% of them would be fitted with CCS (260 GW, mostly in China and the United States) globally. In contrast, only 10 GW of coal power plants would be fitted with CCS in 2040 in the NP scenario. By 2040, the share of gas power plants in total installed capacity would fall to 16% and 20% of them would be fitted with CCS (NP scenario).

3.2.4 Technological development and the role of disruptive technologies

The CPS deals with the penetration of new and more efficient technologies in sectors on the demand side (buildings, households, industry, tertiary sector and transport). However, the documentation of the modelling of technological progress and the consideration of new technologies in the individual models varies widely but does not allow for a detailed description of technological characteristics. In the transformation sector (heat and power generation), new technologies that are currently not mature enough for the market do not appear in the study. Learning curves are given as input to all models of the transformation sector, but no further information on decreasing costs and increasing efficiencies are given. Against the background of the limited information on technological details in the CPS, it can be assumed that potential efficiency gains and economies of scale are included as assumptions in all models but there are no feedback loops of installation rates and cost effects. In addition to techno-economic aspects, the choice of technologies seems to be essentially driven by the normative policy objectives of the study. The ERS describes the penetration and choice of new technologies considered in the Price-Induced Market Equilibrium System (PRIMES) model more explicitly. The model covers both supply and demand side technologies with centralized and decentralized power generation, direct heating and cooling applications, supercritical coal power plants, advanced gas combined cycle plants and cogeneration (CHP), CCS, the 3rd and 4th generation of nuclear energy, advanced transmission and distribution grids and smart metering, plug-in hybrid and battery electric vehicles both for passenger and freight road transportation, improvements in conventional engines in transport, etc. In contrast to the CPS, the ERS reference scenario also provides levelized cost of electricity (LCOE) development of power generation both of RES and non-RES technologies until 2050 and learning curves for demand side technologies which reflect decreasing costs and increasing performances as a function of cumulative production. The EUCO policy scenarios follow more stringent ecodesign standards, but different costs assumptions for technologies are not well documented. In addition, technology learning curves are scenario specific in the majority of the applied models in the ERS. Similarly, the WEO projections are also very sensitive to the way that technological changes affect the cost of different fuels and technologies, including the cost of investing in energy efficiency. The process of learning and cost reduction is fully incorporated into the World Energy Model (WEM), both on the demand and supply sides, and applies not only to technologies in use today, but also to those approaching commercialization. The 450 ppm scenario assumes a higher cost reduction than the NP and CP scenarios, since it is assumed that the more a particular technology is used, the faster the cost reduction. This is also differentiated by country/region. However, the influence of the expansion of technologies on techno-economic parameters is not explicitly modeled in the three studies (but is occasionally taken into account in the scenarios via exogenous assumptions, as in the WEO), but would probably have a significant influence on the expansion (especially in cost optimization models) of the technology portfolio.

3.2.5 Development of future fuel prices

Fuel prices are subject to a high degree of uncertainty due to the availability of resources, demand projections and global climate policies. In the CPS, there is no differentiation among scenarios and an increase of prices between 2015 and 2050 for crude oil by 108%, natural gas by 82% and coal by 71% is assumed, while the price for lignite is assumed to remain stable. Also for the

ERS, there is no differentiation among scenarios and EU28 countries. It is assumed that there would be an increase of import prices between 2015 and 2050 for crude oil by 160%, natural gas by 98% and coal by 190%. The high growth rates are also due to the lowest historical prices (from 2010 to 2015) in the reference year of 2015. In contrast to the former two studies, the prices for natural gas and steam coal in the WEO are differentiated by regions and scenarios for the main import regions or countries. The prices for crude oil are only differentiated by scenarios, due to the existence of a global market. The 450 ppm scenario has the lowest expectations for the growth of future fossil fuel prices, followed by the NP and CP scenarios. The future prices of crude oil would increase the most from 2015 to 2040 globally with 189% (CP), 143% (NP) and 53% (450 ppm) followed by natural gas and steam coal for the EU import prices with natural gas of 86% (CP), 64% (NP), 41% (450 ppm) and steam coal of 54% (CP) and 35% (NP). In the 450 ppm scenario, the steam coal import prices for the EU even decrease by 11% from 2015 to 2040. Thus it can be stated that only the WEO incorporates the interdependencies between fossil raw material prices and scenarios. This may be justified by the fact that in a global analysis the pure price taker approach does not apply (as for example in an analysis for Germany in the CPS). On the other hand, at least for Europe it could be expected that scenarios aimed at a high CO_2 reduction will have an influence on global market prices. Such interactions or uncertainty analyses based on sensitivity estimates are not considered in the CPS or the ERS and might have a substantial influence on the results (e.g. in the choice between hydrogen and fossil fuels in industrial processes and the potentially induced necessary reduction measures in other sectors in both normative and explorative scenarios).

3.2.6 Development of CO_2 prices

Another influential policy variation among the scenarios is the scope and level of carbon pricing, which has a major impact on the relative costs of using different fuels. In general, surcharges on the fossil fuel prices have a strong incentive effect on emission reductions that need to be addressed when developing the climate protection strategy. In both target scenarios of the CPS, CO_2 prices are continuously rising with high ($\$_{2015}$ 188) to very high ($\$_{2015}$ 289) prices in 2050. The policy scenarios in the ERS only focus on policies for efficiency improvement, GHG emissions reduction and increasing RES shares without the discussion of the influence from higher carbon prices (even though PRIMES simulates emission reductions in the European Union Emissions Trading System (EU-ETS) sectors as a response to current and future EU-ETS prices). In the ERS, there is no differentiation (at least not stated in the report) of carbon prices among scenarios. By 2050, the carbon price within the ETS is assumed to be $\$_{2015}$ 100 per ton which follows the trend of the WEO NP. In the WEO 450 ppm the price is assumed to be $\$_{2015}$ 140 per ton in 2040 for the EU28. Even in the most ambitious EUCO+40 scenario, energy-related CO_2 emissions in 2030 (2132 tonnes) could not nearly match those of the WEO 450 ppm scenario (1844 tonnes), which targets a temperature increase of below 2°C. Scenarios that only have a short to medium-term perspective thus carry the risk that they will not be consistent with the global long-term climate goals or discard the potentially higher regional transition costs after 2030.

The WEO only accounts for energy related CO_2 emissions while the ERS also accounts for non-energy related CO_2 emissions and non-CO_2 greenhouse gas emissions, which are subdivided by two policy frameworks of the EU-ETS and Effort Sharing Decision (ESD) covering sectors. The CPS also considers greenhouse gas emissions from land use, land use change and forestry (LULUCF) (for a detailed analysis of differences from model structures, see Sections 3.3.2 and 3.3.3).

3.2.7 Data requirements

Requirements for the model parameterization and for the definition of the input data for the scenarios depend strongly on the sectoral, technical, spatial and temporal resolution of the studies. While the analysis of the CPS is only carried out at national level, the ERS provides energy balances for 28 EU member states and the WEO for 25 world regions and countries. However, the CPS has mostly a much higher resolution of demand sectors, for example with regard to the building sector or the consideration of industrial processes. Only occasionally the study provides information on the spatial resolution of the models and to what extent regionally differentiated information is incorporated.

The WEM as a large-scale simulation model states to have a considerable sectoral and technological resolution as well, but data requirements and data used are mostly not provided for sub-models or in high granularity. The ERS also uses models with considerable differentiation of processes on the demand and supply side. The study mentions the resolution of the data, but how they were used in detail must be identified by additional model documents.

3.2.8 Input and output data access

Especially the input data is not provided in a fully transparent way. Even though the studies present some sources for the input data used (see Table A in the Supplementary Material for the main data sources), they are not presented adequately. For example, the CPS study mostly lists data sources in the text or under the tables which are sometimes provided for specific numerical input data. However, this forces the reader to search any cited source for the corresponding numbers or, in case of doubt, to choose between numbers that have the same information content. The ERS describes input data using developed storylines and models. Some sources are available to explain the input data, but a more detailed database must be used for model-specific documents (e.g. for the PRIMES model). In the WEO, input data are also not fully provided. Similar to the CPS, multiple sources are often listed for a certain parameter so that readers cannot track specific data values. Furthermore, some input data stem from their own IEA database (with links provided), but further guidance on how to use the database might be necessary for readers. In all three studies, main results are always provided in tables or figures, which contribute to the understanding for the reader. However, the data is not available in the maximum resolution of the modeling results.

From a scientific point of view, researchers would benefit more from scenario reports for future research if data requirements of the studies could be clearly presented. This especially holds true for the level of data aggregation and their temporal and spatial resolution, which are often unavailable for the reader. By publishing detailed information on input and output data (such as in supplementary materials or open data platforms), scientists in particular could be compensated for the partial lack of information on the applied models (because the structure and functionality of models can be partially derived from details on data).

3.3 Applied methods and models

In the following sections, the three scenario studies are compared with regard to their core methodological aspects on the basis of Table A 1 in the annex in combination with specific findings about the applied models and the transparency of the input and output data provided. All three studies follow an advanced scenario building approach, but are different in many aspects. However, due to the limited transparency, in particular with regard to applied models and model coupling and the associated input-output data, it remains difficult to assess the methodological robustness of the three studies.

3.3.1 Analytical approach and methodology

Against this background, we follow a systematic approach for characterizing the traceability of the studies and their analytical approaches covering the aspects framework assumptions, resource supply, fuel processing and supply, energy conversion, network and flexibility options, end-use sectors, and emissions and pollutants. With this representation of model-based scenario analysis, we graphically capture the main components with regard to the applied methodology (e.g. top-down or bottom-up approach) and in particular the transparency and presentation of the input and output data (input data: e.g. from database, statistics or literature; output data: e.g. results of general calculations/data processing from the applied models). In order to represent the complexity of the scenario studies in a well-structured figure, we defined some acronyms with clear rules for the classification of model parts:

Assessment methods

- We mark aspects of the studies as not available (**N/A**) if the study mentions certain components of the modeling framework and takes them into account in the analysis. Hereby, the modelling/underlying assumptions of the analysis are not described sufficiently (e.g. only mentions them qualitatively).
- We mark modules of the study as available (**A**) when input-data is directly used without significant processing.
- We mark data/results that come from internal model based assessments (**M**). A component not included in a study (e.g. due to a different scope in a study) is marked with "**/**".

Data

- We highlight a clear naming of the source for the individually used input data (**I**), otherwise we define it to be not provided (**NP**). This also holds true for data exchanges in model-coupling (see also Fig. 2).
- A clear naming and representation of output data/processed data is defined as well illustrated output (**O**), otherwise we define it to be **NP** (see also Fig. 2).

It has to be mentioned, that the resulting figure does not describe internal model links (e.g. between different models in studies with model coupling).

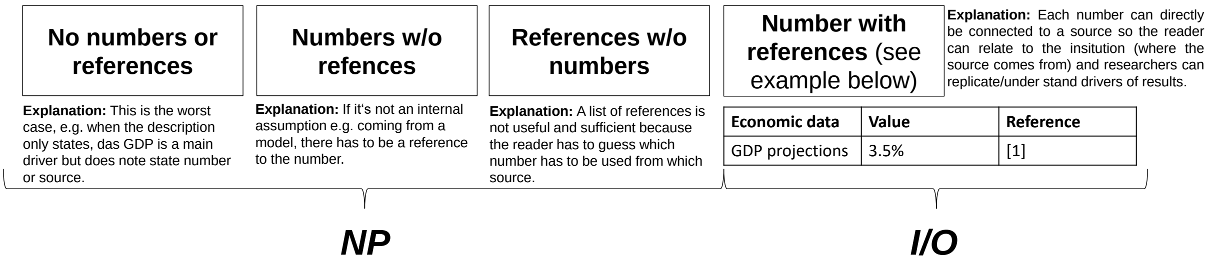
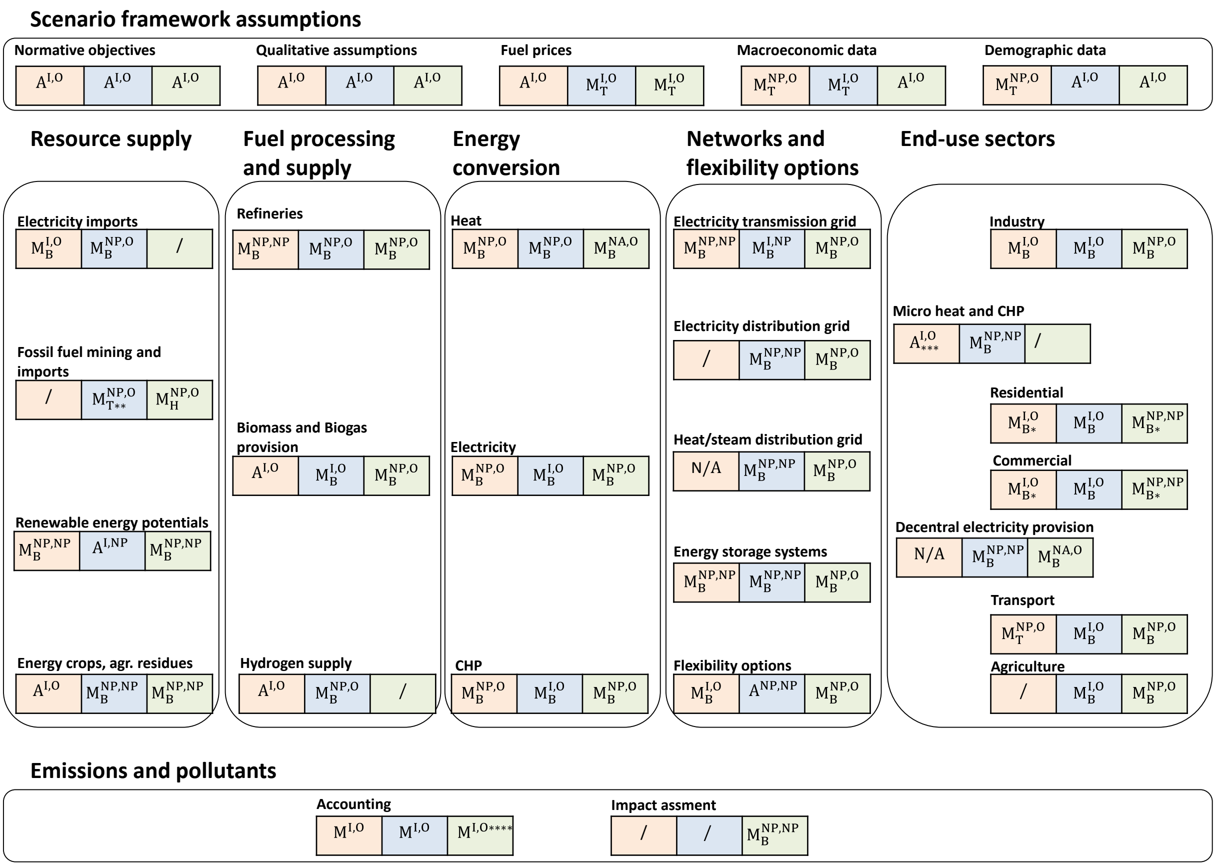


Fig. 2. Background information on the figure: rules for a sufficient description of input and output data.



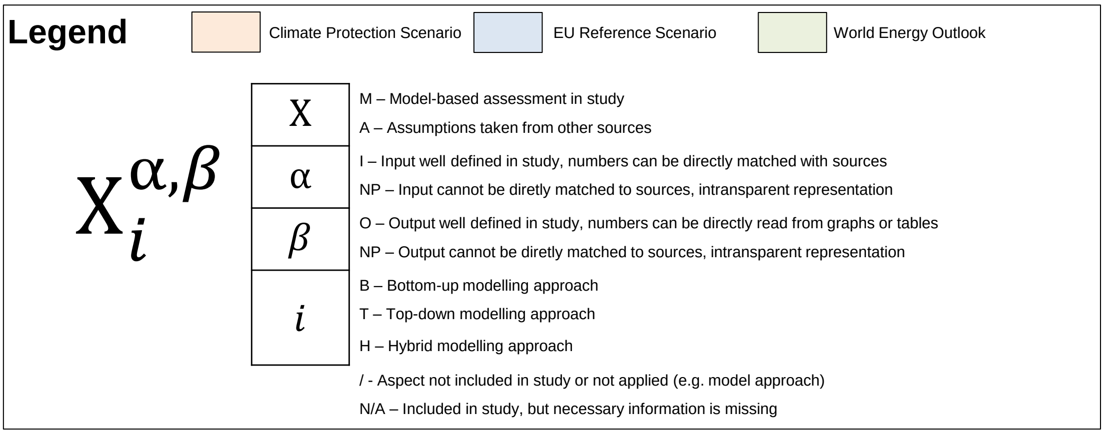


Fig. 3. Graphical representation of the traceability assessment for the three scenarios. Indication of the consideration of partial aspects: *Aggregated as building sector, **Gas sector only, ***Provided for heat pumps only, ****CO_2 Emissions only.

Fig. 3 presents our evaluation results in a condensed format (more information can be found in Table A 1 in the annex, especially with regard to technological resolutions and model structures). The following sections provide an in-depth discussion of significant methodological aspects of scenario construction.

3.3.2 Applied models and purpose

A critical aspect regarding scenario transparency is the documentation of methods and models applied for the scenario studies. The CPS describes the models shortly, without further literature for more detailed information, while the ERS and the WEO have comprehensive separate study specific model reports online, e.g., for the PRIMES and the WEM model respectively (see Table 1).

General framework assumptions such as normative objectives are usually not based on model results, but are derived from other studies, official policy objectives or defined within the consortium. Quantitative scenario drivers such as fuel prices, macroeconomic as well as demographic development are either determined by assumptions or model-based calculations. While the developments of fuel prices in the CPS are taken from other studies, these are calculated using models in the ERS as well as in the WEO. Hereby, the ERS study uses a global partial equilibrium ESM that endogenously derives consistent price trajectories for oil, natural gas and coal based on the evolution of global energy demand, resources and reserves, extraction costs and bilateral trade between regions. The WEO uses a top-down economic equilibrium approach to calculate the output of coal, gas and oil that is stimulated under the given price trajectory. Feedback loops between demand and supply take place until the equilibrium is attained. In the CPS and the ERS, macroeconomic data (sectoral developments aggregated to GDP) are derived on the basis of top-down equilibrium models, while the WEO uses assumptions for GDP development. Also the demographic development in the CPS study is calculated by a top-down model with Input-Output Tables at its core. However, the study does not explain how this model is used to calculate demographic trends. In contrast, the ERS and the WEO work with assumptions derived from secondary literature for this scenario driver. In general, the use of models to quantify scenario drivers within the consortium may provide the chance for potential model interactions between the scenario analysis framework and price sensitive models, which in principle can improve internal consistency (e.g. by considering to which extent the results of macroeconomic models are affected by the level of energy demand, implemented technologies or electricity prices of the individual transformation paths). However, this does not seem to be taken into account in any of the studies on macroeconomic and demographic developments (the CPS only carries out an ex-post assessment of the scenarios with regard to these variables). An exception to this with regard to commodity prices is the WEO, which assumes scenario-dependent price paths.

Electricity as a resource (imported) is only relevant for analyses of limited geographical areas (as it is the case only in the CPS). In the CPS these are calculated using an additional supranational bottom-up optimization model for the Europe, Middle East and North Africa (EUMENA) region. The ERS applied bottom-up optimization models to study the EU internal electricity market (no electricity exchange with countries/regions outside the EU-28) while in the WEO the power generation module ensures that enough electricity is generated to meet the annual volume of demand in each region (thus no electricity exchange is considered for each modelled region). While fossil fuel mining and imports are not modeled in the CPS (Germany as price taker), the ERS uses a gas supply module which calculates gas imports by country of origin, by transport means (LNG or pipeline) and route as well as wholesale gas prices for the EU member states. The WEO, however, contains detailed modules for oil and gas to project the level of production and trade and a module for coal to assess the remaining recoverable resources for the model regions. Renewable energy potentials for wind and PV power plants are calculated using a GIS-based bottom-up approach in the CPS. However, these profiles only seem to be considered in the supranational model used for electricity in- and export modeling. In the ERS, renewable potentials are based on various sources while the WEO has a sub-module for RES to calculate dynamic cost-potential curves (which include technological learning) for electricity supply from RES (such as bioenergy, hydropower, PV, concentrated solar power (CSP), geothermal electricity, wind, and marine). The use of energy crops and agricultural residues is not modeled in the CPS and the ERS but is based on various other sources and databases providing constraints on potentials and various sectoral allocation methods. In contrast, the WEO uses a bioenergy supply module which enables the calculation of the biomass feedstock supply by region. From this it can be deduced that the modelling of fossil primary energy carriers is only conducted if, for example, the individual regions also have a potential influence on global demand and prices. The smaller the geographical area, the smaller the potential effects on the world market and the more likely it is to use assumptions from global projections. On the other hand, the higher the regional resolution in the models, the higher the potential exchange of electricity between regions and the associated need to model these energy flows.

Fuel processing and supply, refineries and other conversion plants (e.g. biofuel production, other refining plants) are modelled independently of the power generation sector (on an annual basis) in the CPS. However, the modeling approach lacks a detailed description and cannot be compared with approaches applied in other studies. In the ERS, an oil supply model is used to project domestic components of petroleum product prices, refining activities and refinery capacity expansion. Biomass and biogas provision are not model-based in the CPS and derived from the potential of energy crops and agricultural residues. In the ERS, a biomass model is used to transform biomass feedstock (primary energy) into bio-energy commodities (secondary or final form) used as input for the energy system (such as for power plants, heating boilers or as fuel for transportation). In the WEO, a bioenergy supply module is included to assess the ability of the WEO regions to meet their demand of bioenergy for power generation and biofuels with domestic resources. It also allows for an international trade of solid biomass and biofuels between world regions. This modeling of the international trade of biomass and biofuels is not considered in the CPS and the ERS.

The modelling of hydrogen production and other process chains (such as methanation) are modelled in the CPS by a pure increase in electricity demand, whereas in the ERS a hydrogen supply sub-model is used to incorporate a large number of technologies for hydrogen production, storage, distribution and end use. The inclusion of infrastructure costs in the large scale use of hydrogen (or derivatives) in transport, industry and power generation can significantly influence the model results. The exogenous specification of an additional demand suggests that this aspect is not taken into account in the CPS but considered in the ERS. In the WEO, the production of hydrogen is not specifically considered and modeled.

Regarding energy conversion, flexibility and infrastructure, a model group of three models is used in the CPS: one is for the import and export modelling of electricity between Germany and the EUMENA region, in which a potential expansion of grid transfer capacities and energy storages is also considered. The expansion and operation of power plants and flexibility in Germany is modelled separately, while one model simulates the expansion of power plants and another model optimizes the economic dispatch in hourly resolution (including CHP plants), whereby flexibility options (such as flexible hydrogen production, storage systems) are also mapped (capacities exogenously given). However, the grid infrastructure within Germany is not modelled (Germany modelled as a “copper plate”). The ERS uses a bottom-up optimization of energy supply that simulates energy market equilibrium in the EU and each of its member states in five year steps and with a sectorial optimization for the heat and the power sector. The model calculates infrastructural needs in terms of electricity transmission and distribution grids, heat/steam distribution grids and energy storage systems including hydrogen generation. The power market and the steam/heat market are simulated simultaneously to capture trade-offs between cogeneration/CHP and condensing power plants, and between self-production and distribution of steam/heat. The transmission grid is modeled as entire system of interconnectors in Europe as well as possible Alternating Current (AC) and Direct Current (DC) line extensions including optional remote connections with offshore wind power in the North Sea and with North Africa and Middle East. Highly distributed generation at consumer premises is also included and is taken into account in calculating transmission/distribution losses and costs. The WEM uses a combined approach whose principle is very similar to that used in the CPS. The type of new generating capacity to meet demand is calculated by a simulation model which uses the regional long-run marginal costs (LRMCs) as decision variable for investments in conventional (including CHP) and renewable power plants. Investments into the transmission grid are a function of demand increase and additional transmission network costs are derived based on specific renewable grid integration costs. An hourly bottom-up dispatch (no expansion) model provides further insights into the operation of power systems with high shares of fluctuating RES. The analytical approach considers the need for storages and demand side management measures (DSM) but excludes the expansion of power grids within the regions. Mini- and off-grid power systems are also integrated into the WEM model with choosing available technologies based on their regional long-run marginal costs.

It can be inferred that electricity transmission grids and energy storage systems are all modelled in the studies as a methodological extension of scenario analysis. However, the modelling of the electricity grid as well as the generation of results and analytical statements are clearly different. While the CPS does not model grid congestion and related costs within Germany, the costs for grids are integrated in the WEO using a heuristic approach. Here, too, there is no cost-optimal network expansion. In ERS, on the other hand, grid expansion of the network infrastructure between the individual countries is cost optimal. However, all three studies do not include an in-depth analysis of security of supply under the conditions of the transformation scenarios.

3.3.3 Model coupling and model structures

All study reports provide graphical overviews of the models/modules involved, the general interplay and their assignment to partial components of the energy system. However, it should be noted that such a representation never fully captures the interaction between models. In all three studies, hybrid modeling approaches are applied for specific sectors or inter-sectoral dependencies. Examples of a sector specific model coupling are the transport models in the ERS and the three-step approach (separate capacity expansion and dispatch models) for the electricity sector in the CPS. The former combines econometric and engineering approaches for deriving transport activity by transport mode and model interactions seem to make sense from a scientific point of view. However, the three-step approach for the electricity sector in the CPS study is conducted in such a way, that electricity imports to Germany (also including capacity expansion planning) are derived from one specific model including the EUMENA region, while capacity expansion and dispatch for Germany is calculated by other two specific models. It seems very difficult to achieve consistency with such a modelling approach, and comprehensible explanations are missing for the most part. Furthermore, model coupling regarding different sectors, especially power to heat, power to gas and power to transport to deal with fluctuating RES and multi-sector electrification becomes a more and more important issue to decarbonize the whole energy system. However, the linkage of the models in terms of model based input and output and external assumptions is not always clearly stated in the studies. From a scientific point of view, satisfactory reasons for the inclusion of models are often not given.

An example of model coupling between naturally largely independent model types is the integration of macroeconomic data derived from top-down models for the calculation of driver variables such as GDP growth or population development. However, the model linkage (e.g. soft- or hard-linked) in terms of input and output data and the harmonization of assumptions is mostly poorly described in the three studies, even with supplementary model documents. Further, information about iterations among models which may be pivotal for the resulting policy advice is insufficiently presented. For example, it can be assumed that the integration of modeled future electricity prices into macroeconomic modelling has a major influence on the relevant drivers of economic growth which influences demand, e.g. for energy and transport related activities (included as ex-post assessment in the CPS). However, only the ERS provides this information on model iterations. This analysis suggests that efforts to achieve consistent model coupling in terms of data and iterations may also depend heavily on whether the models originate from one institution/group or whether data needs to be exchanged between numerous institutions/groups.

3.3.4 Model validation

The general understanding of model validation is the detailed discussion of model strengths and weaknesses (parameters, variables, formulation, etc.) and to compare the model results to real-world data. The idea of validation here is also to verify if the models are performing as expected and if they are in line with their objectives. The validation tests to check models' output can be performed internally (self-validation included in the study) and externally (feedbacks from other researchers or media). However, none of the three scenario studies state how far the models are validated. Only limited output data were calibrated with similar studies internally. For example, the ERS validates forest harvest removals by calibrating them to the most recent FAOSTAT data from the year 2015. Furthermore, economic and transport activity projections are validated by typical indicators such as GDP or activity per capita. External validation is often reflected by scientific and public perception, this, of course, is outside the focus of our analysis. Although the scenarios of the three studies are used as basis for other researchers in academia and the WEO is also cited by public media positively, some criticism can still be found. For instance, [26] reviewed the methodology of the IEA WEO studies and provided a critical assessment of key assumptions and projections. The authors argued the IEA may introduce a conservative bias with a neglect of dynamics and interlinkage in the energy and economy nexus. In general, the authors of the three studies could provide more reasons for making assumptions, selecting data, building and applying models, defining scenarios and testing against real world data. These efforts would contribute to internal validation. Public perception, as external validation, would be considered for future research.

3.3.5 Uncertainty treatment in the model and reporting

All three studies present and analyze scenario variants that show different possible developments. However, there is no explicit discussion of uncertainties in the various assumptions and in the use of models to answer the research questions. In addition, the pathways presented only represent a very narrow selection of possible future developments, for example with regard to the development of the economy, the mobility, and the society as a whole. This is due on the one hand to the defined narratives and implicit socio-economic assumptions and on the other hand to the cost-optimizing approaches of modelling, in which cost effects dominate and steer the developments. Assumptions of disruptive factors and elements are missing to a large extent and thus also the possibility to check the robustness of the model results and the conclusions and policy recommendations derived from them. Regarding the different modelling approaches we found no documented sensitivity analyses showing effects of variations on the side of model parametrization. In general, however, the studies do not provide qualitative or quantitative reporting on uncertainties or explicit sensitivity analysis for individual scenarios and contain only general comments on uncertainties mentioned in the model descriptions.

3.4 Further aspects

From a societal perspective, all studies neglect several relevant aspects and do not consider or document significant implicit assumptions. In the case of the former, this concerns, as mentioned above, the definition of only one single path for key economic and social drivers. Significant other aspects concern the lack of feedback processes from the change of energy use and generation to the economy as well as the lack of consideration of possible disruptive developments. Only the CPS carries out an ex-post assessment of the change in GDP and employment between the EMS and the CS 80 scenario.

In the case of implicit assumptions, this concerns the assessment of the relevance of social factors and risks or the development of technologies and their market implementation as well as required investment incentives for relevant actors. Assumptions or prerequisites regarding the development of political framework conditions are also not sufficiently discussed and integrated into the scenario context, for example with regard to stronger national, European or even global integration of energy policy or possible effects of increasing isolation and confrontation in foreign policy. These aspects may lead to inconsistencies in both methodologies and input data. With regard to the development of technologies and their costs, the studies largely avoid speculative assumptions. As far as this is documented and traceable, the technological innovations considered are in the range of what corresponds to today's or from today's point of view achievable state of the art. However, rather speculative assumptions concern, for example, assumptions about future consumption by the population, a renaissance of nuclear power, or the possible impact of political measures.

The publication of the studies in the form of final reports also shows clear differences. This concerns for example the active information of the public via press releases and events and the suitability of the publications either for the information of the interested public or as basis for further scientific scenario analyses. Common to all studies is the lack of parallel scientifically relevant publications in peer-reviewed journals and thus a scientific discussion of the scenario construction. In most cases, however, this is the case for the methods and models used. Nevertheless, all studies are used as framework scenarios for scientific studies or expert opinions and are therefore often cited by academia and media.

4. Recommendations and Implications for scenarios developers

Based on our assessment of the three scenario studies, several recommendations can be deviated that extend the more theoretical transparency checklist by Cao et al. [27].

4.1 Further improvements of model transparency

4.1.1 Provide supplementary documents with well documented input-output data

As discussed above, the input-output data are not fully transparently documented. One reason might be that the core problem with energy data is that they are usually seriously protected. But a more precise description of which data is used might improve the reproducibility and transparency of the model and resulting scenarios. An option could be sometimes to publish simulated/artificial data, which uses the main characteristics of the original data, but blur critical issues such as business relevant information. Validation of this artificial data is however crucial and complex. For example Wiese et al. [28] provide a significant attempt aiming to provide a unique open power system dataset for Europe, which might be used as a reference input to ESMs in order to improve the comparability of their results. For example, Hirth et al. [29] argue similarly for an open data access and a recent tool allows to evaluate the quality of input-data [30].

4.1.2 Explain model linkage and data exchange

Model coupling with either the same focus on one sector or different focuses across sectors is widely applied in large scale energy system scenario studies. Our analysis shows that the description of the model-exogenous input data and their processing and exchange are in most cases not sufficient, since data integration into the models is hardly comprehensible for outsiders. This is especially true for studies with model-couplings, which transfer comprehensive data volumes between the different models (as e.g. seen in the ERS and the CPS). Therefore, a description of the data flow in combination with the corresponding model architecture could be helpful for the research community to fully understand the results of the study. Furthermore, the information whether models are soft- (i.e. manual data transfer between models) or hard-linked (i.e. direct data transfer between models) gives information about the complexity and the error-proneness of the coupling. However, the pure knowledge about the model coupling approach and the data exchange is not enough. Lessons-learned publications for all coupling efforts with detailed descriptions of approaches used, data exchange within these approaches, and difficulties would be helpful for future work (as e.g. in [31]).

4.1.3 Provide full open source and well documented model codes

All three reviewed studies do not provide open source model codes. Already in 2012 the requisition for well documented model codes were claimed by Laugs and Moll [32], [33]. In the following years several other contributions to literature occur. For example, Morrison [34] views open source models as one core aspect for public transparent and scientific reproducible energy system modelling. The author focuses on legal aspects of existing open access models. Pfenninger et al. [35] already provide a comprehensive overview of current open source ESMs with a focus on open data. The authors indicate that the current trend is overwhelming even though the energy sector seems to lag behind other computer model societies. This optimistic perspective is supported by current grass root developments such as openmod-initiative.org. The main advances of open source codes are besides the reproducibility and transparency, the easy comparability of scenarios and the higher efficiency in developing high sophisticated and broadly approved ESMs [36], [37]. The hope is when providing source code and data publicly swarm intelligence might speed up developing processes significantly. Another positive side effect is the broader acceptability in the scientific community.

4.2 Further improvements of scenario consistency and robustness

4.2.1 Societal context scenarios

An important weakness of most techno-economic energy scenarios is the lack of uncertainty and complexity in the social context. Several social factors that influence the development of energy supply and demand are usually not explicitly addressed in scenario reports, e.g. cultural influences on the acceptance of change processes or political and state specifics in change processes and their effects on interest groups. Combining explicit, qualitative and quantitative context storylines and energy modelling in a consistent and transparent way could significantly help to improve the robustness of scenario results and conclusions (see e.g. [38]). This may lead to the construction of comprehensive socio-technical scenarios considering crucial aspects of the energy transition such as disruptive elements attributable to societal risks or opportunities [39]. The construction of socio-technical scenarios as 'hybrid' scenarios can in the future combine both perspectives and methodologies for the formation of a truly interdisciplinary modelling approach [40].

4.2.2 Stakeholder integration

Stakeholders can be involved either during the scenario creation process or subsequently by communicating the results (e.g. via publications or online accessibility). However, the inclusion during the scenario creation process did not take place in any of the studies. In the last decades stakeholders were only included in scenario building from time to time, e.g. for discussing specific parameters for power plants with utilities or for public participation in local or regional government planning. Today arguments for including more stakeholders and even the consumers become more important [41]. The inclusion of stakeholder opinions might be "measured" in workshops (see e.g. [42]), while the inclusion of consumers usually requires surveys (see e.g. [43]). Most of the energy scenarios and policies derive from complex techno-economic analyses, but have difficulties in taking into account other types of relevant societal values and interests (see also [44], [45]). In this context, public perspectives can provide insights into potential societal opportunities and limitations of energy pathways and, in particular, answer the question of which aspects and configurations of system change will provide a socially acceptable level of affordability, energy security, and environmental protection.

4.2.3 Uncertainty analysis for key input data

The three reviewed policy-oriented scenario analyses have not provided uncertainty analysis for key input data, which reduces the robustness of the derived results considerably. In principal, an identification of relevant uncertainties can be drawn from a sensitivity analysis, which intends to identify key driving forces. A stochastic approach is a way to include small (and well understood) uncertainties of input data, e.g. by Monte Carlo simulations, if the computing times allow multiple model runs. More unknown and more significant uncertainties might be considered by different scenario variants. Recent studies show that sensitivity analysis is widely used to analyze the macroeconomic parameters (e.g. [46]), energy technology costs as a prerequisite to determine investments (e.g. [47]), and technical parameters related to multiple research questions (e.g. [47]). The stochastic approach is mostly used for renewable energy system optimization, e.g., for multi-criteria system design [48] or to deal with the uncertainty in the availability of renewable resources [49].

4.2.4 Common model structures and open data

We found that it is rather difficult to compare and assess scenario studies mainly due to different formulation of storylines, applied approaches and model structures, and related data. Different focuses in ESMs used for similar tasks could lead to different outcomes and conclusions. On the one hand, model diversity can help us to gain a comprehensive understanding of the energy system transformation. However, on the other hand, this makes it difficult to understand and compare the results. Non-transparent data sources and model descriptions add additional difficulties for assessing the analysis and the quality of derived policy recommendations. A joint definition of common model and data structures could improve the situation and provide advanced, open source reference methods and parametrizations. Such a task could be organized by an international organization but requires multinational financing and widely participation of the academic community and other stakeholders for providing data and sharing experience and perspectives.

5. Conclusions

Our review demonstrates that fulfilling the criteria of transparency, comprehensibility and traceability requires a clear concept and certain effort of documentation as well as a feasible way of providing detailed data and information. By means of a graphical and tabular summary of the studies and further discussion and evaluation, we have attempted to capture essential aspects. The results confirm that each model-based scenario study has strength and weaknesses and vary significantly regarding the use of methods and models. Scenario studies often neglect aspects which can hardly be quantified such as societal and environmental risks and opportunities or only reflect a very restricted spectrum of possible developments, e.g., with regard to drivers of the energy demand. Furthermore, it is difficult or even impossible to evaluate scenarios and their methodological background only based on a final report. All three studies thus refer to background material, i.e. documentations of the models used or to studies from which results are used as assumptions for model parameterization. Obvious weaknesses identified are the weak transparency about model coupling and data access, widely lacking of sensitivity analysis for key assumptions. The effort required to get a clear picture here is unacceptable for interested addressees of these reports. While the studies often present graphs for the understanding of applied models and their results, they often insufficiently describe model interfaces and data exchange, the harmonization of assumptions as well as iteration loops between the models. Furthermore, little information on model validation is given and comprehensive uncertainty analysis of key assumptions is missing. Thus, the necessity and suitability of model usage with regard to the research questions remains largely unclear to the reader. Therefore, more well-documented open source and open data studies are desirable in the field of energy systems analysis. Moreover, the authors of scenario studies must pay more attention to making their results comprehensible to the general public and to openly discussing the robustness and uncertainties of their conclusions and policy implications.

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Annex

Table A 1: Detailed results of the scenario review

Category	Analysis items	German Climate Protection Scenario 2015	International Energy Agency - World Energy Outlook 2016	European Commission Reference Scenario & EUCO Policy Scenarios 2016
Scope & purpose of analysis	**Authors, Institutions**	28 authors listed. • Öko Institut: J. Repenning, L. Emele, R. Blanck, H. Böttcher et al. • Fraunhofer ISI: S. Braungardt, W. Eichhammer, R. Elsland et al. • H.J. Ziesing	> 40 contributors, >200 reviewers. • WEO team of IEA-STO: L. Cozzi, T. Gould, M. Baroni, B. Wanner et al.	27 authors listed, > 30 contributors. • E3M-Lab of Department of Electrical and Computer Engineering, National Technical University of Athens: Prof. P. Capros, A. De Vita, N. Tasios, P. Siskos, M. Kannavou, A. Petropoulos, et al. • Institute for Prospective Technological Studies of Joint Research Center, European Commission: L. Paroussos, K. Fragiadakis, S.Tsani, P. Karkatsoulis et al. • International Institute for Applied Systems Analysis: L. Höglund-Isaksson, W. Winiwarter, P. Purohit, A. Gomez-Sanabria et al. • European Centre for Agricultural, Regional and Environmental Policy Research: H. P. Witzke, Monika Kesting
	Aim and funding	**Aim:** to show possible pathways towards a reduction in greenhouse gas emissions (GHG) in all relevant sectors according to the targets of the German government. **Funding:** BMUB (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)	**Aim:** to inform policy makers where current policies and policy ambitions may lead the energy sector as well as which policies are needed to achieve the goal of limiting the average global temperature increase and to provide first comprehensive examination of the new era opened up by the Paris Agreement. **Funding:** autonomous agency IEA (International Energy Agency) and its 29 (30) members (OECD countries)	**Aim:** the reference scenario acts as a benchmark of current policy and market trends on the EU energy system, transport and GHG emission developments, which can help to inform future policy debate and policy making among all EU28 member states (e.g. derived EUCO policy scenarios till 2030). **Funding:** Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport from the European Commission

	Geographical scope	Germany	Global, region wise (10 world regions), and selected countries	EU28, country wise
	Time horizon	Until 2050	Until 2040	Until 2050 (reference scenario), until 2030 (EUCO policy scenarios)
	Scenario names, types (normative/ explorative) and aims	• Business as usual scenario (EMS, explorative): extrapolates the policies from 2012 till 2050. This means that policies are not updated or further developed according to the actual development/discussions but will stay the same until 2050 • Climate protection 80 (CS 80, normative): the greenhouse gas emissions are decreased by 80% by 2050 (wrt 1990) • Climate protection 95 (CS 95, normative): the greenhouse gas emissions are decreased by 95% by 2050 (wrt 1990)	• Current Policies Scenario (CP, explorative): extrapolates current actions and trends (as of mid-2016) till 2040 • New Policies Scenario (NP, explorative): assumes the implementation of policy announcements and plans until 2040 (e.g. current aims, targets and intentions) • 450ppm Scenario (normative): has the objective of limiting the average global temperature increase by 2100 to 2°C above pre-industrial levels	• Reference scenario (REF, explorative): trend projections, legally binding GHG and RES targets for 2020 are achieved and policies agreed at EU and Member State level till 12/2014 implemented • EUCO27 (normative): achieves 27% RES share and 27% reduction of primary energy use in 2030. GHG reduction (wrt 1990) >40% • EUCO30 (normative): 27% RES share and 30% reduction of primary energy use in 2030. GHG reduction (wrt 1990) > 40% • EUCO+33 (normative): built on EUCO30 with higher efficiency target up to 33%. GHG reduction (wrt 1990) 43% • EUCO+35 (normative): built on EUCO33 with higher efficiency target up to 35%. GHG reduction (wrt 1990) 44% • EUCO+40 (normative): built on EUCO35 with higher efficiency target up to 40%. GHG reduction (wrt 1990) 47% • EUCO3030 (normative): 30% RES share, 30% reduction of primary energy use in 2030. GHG reduction (wrt 1990) 43%
	Storyline behind scenarios	• **Demand drivers:** are not differentiated by scenarios. Average annual GDP growth rate of (0.8%/yr), decrease in population (from 81 to 74 million). The number of households grows slightly until 2040 and then decreases by 2% until 2050. • **Final energy demand:** decreases strongly by 2050 esp. in the normative scenarios (23% (EMS), 38% (CS 80), 49% (CS 95)) according to efficiency targets.	• **Demand drivers:** are not differentiated by scenarios. Population grows in most world regions (globally from 7.3 to 9.2 billion with an average growth rate of 0.9%/yr from 2014 to 2040, especially in Africa, India and Middle East). The population in EU28 increases slightly from 570 million (2014) to 599 million (2040) with an average growth rate of 0.2%/yr. Urbanization rate increases from 76% to	• **Demand drivers:** are not differentiated by scenarios. Population grows from 505 million to 522 million for EU28 (2015-2050) with an average growth rate of 0.1%. Population in Germany decreases from 81 million to 75 million. No information available for urbanization rate. Average GDP growth rates from 2015 to 2050 are 1.9% for EU28 and 1.1% for Germany. • **Final energy demand:** decreases only by

		• **Electricity demand:** decreases until 2030 due to efficiency targets but increases again due to electric mobility and hydrogen demand (esp. in CS 95). The increase rates from 2015 to 2050 are 13% (EMS), 7% (CS 80) and 11% (CS 95). • **Renewable energies:** strong growth in normative scenarios, especially for power generation (>90%). By 2050, the share of RES in primary energy supply reaches 41% (EMS), 67% (CS 80), and 89% (CS 95). • **Fossil fuels/nuclear:** substitution of coal and oil with gas, expansion of cogeneration (CHP), nuclear phase-out after 2020. Coal would be still used in 2050 in all scenarios. CCS would be used only in CS 95 and only in industry and biomass combustion from 2030 on. The capture rate is well below 50 Mt CO_2/yr in all scenario years of CS 95. • **Biomass use:** limited according to estimated sustainable potentials, use above all in transportation sector. The share of biomass for primary energy supply would increase from 11% in 2015 to 19% by 2050 in normative scenarios while in the EMS the share would stay rather stable with a reduction of use over scenario years. • **Technology development:** the CPS deals explicitly with the penetration of new and more efficient technologies in sectors on the demand side (buildings, households, industry, tertiary sector, transport). The long-term application of so far not commercially proven technologies such as CCS, the provision of heat via large-scale electricity (power-to-heat) or the production of synthetic fuels via PtX (power-to-gas; power-to-liquid) are	82%. Average global GDP growth is 3.4%/yr and 1.6%/yr for EU28. • **Final energy demand:** increases by 45% (CP), 34% (NP) and 14% (450ppm) from 2015 to 2040 globally. In CP no obvious decrease from 2015 to 2040 for EU28 while there are reductions of 11% in NP and 22% in the 450ppm Scenario. • **Electricity demand:** increases by 79% (CP), 65% (NP) and 47% (450ppm) from 2015 to 2040 globally; for EU28 the increase rates are lower: 23% (CP), 11% (NP) and 8% (450ppm). • **Renewable energies:** RES share in power generation reaches 29% (CP), 37% (NP) and 58% (450ppm) globally by 2040. In EU28, RES share in power generation reaches 43% (CP), 53% (NP) and 63% (450ppm) by 2040. The share of RES in primary energy supply grows to 16% (CP), 19% (NP) and 31% (450ppm) by 2040 globally and 23% (CP), 28% (NP), 37% (450ppm) for EU28. • **Fossil fuels/nuclear:** nuclear renaissance in all scenarios with 9% (CP), 12% (NP) and 18% (450ppm) shares of power generation globally. CCS is implemented after 2025 and achieves max. 4% (450ppm), thereof 60% coal-fired. This relates to 260 GW coal power plants with CCS, mostly in China and USA, by 2040. In the NP scenario, only 10 GW of coal power plants are with CCS. Power generation from coal decreases from about 40% in 2015 to 36% (CP), 28% (NP) and 7% (450ppm) in 2040, resp. • **Biomass use:** both the share and utilization of biomass would increase globally and for EU28 in all scenarios. The share of biomass for primary energy supply would change from 10% in 2015 to 9% (CP), 11% (NP) and 16% (450ppm) by 2040 globally and would	4% for EU28 and 15% for Germany in the REF case from 2015 to 2050; decreases by 9 - 27% for EU28 and by 14% - 32% for Germany from 2015 to 2030 in the EUCO policy scenarios. • **Electricity demand:** increases by 28 % for EU28 and 11% for Germany from 2015 to 2050 in the REF case. The EUCO policy scenarios result in -6% to 10% for EU28 and -8% to 7% for Germany. • **Renewable energies:** the REF scenario reaches a RES share for power generation of 55% in EU28 and 60% in Germany by 2050. The share of RES in primary energy supply for EU28 and Germany is less than 30% by 2050. RES shares for EUCO scenarios see above. • **Fossil fuels/nuclear:** nuclear phase out for Germany after 2020. The share of power generation from nuclear decreases for EU28 from around 23% in 2015 to 18% in 2050 in the REF. Fossil fuels with CCS would be implemented after 2020 for EU28 but not for Germany. The share of CCS in installed capacity of fossil fuel power plants would reach up to 5% by 2050 for EU28. The generation share of coal decreases from 23% in 2015 to 6% in 2050. • **Biomass use:** both the share and absolute use of biomass would increase for EU28 and Germany in the scenarios. Biomass share of primary energy in EU28 increases from 8% in 2015 to 12% by 2050 and from 9% in 2015 to 13% by 2050 for Germany in the REF scenario. • **Technology development:** the ERS describes explicitly the deployment of new technologies considered in the PRIMES model, which covers supply and demand side with centralized and decentralized

		assumed. However, the description of the modelling of technological progress and of the consideration of new technologies in the individual models varies widely and does not provide detailed technological characteristics. In the transformation sector (heat and power generation), technology learning curves are given as input to all models, but no further information is available. Given the sparse information, it can be assumed that efficiency gains and economies of scale are included as assumptions in all models (without feedback loops between installation rates and cost effects). In addition to techno-economic aspects, the choice of technologies seems to be essentially driven by the normative objectives of the study. Furthermore, no detailed description of new and potentially disruptive technologies is given. • **Fuel prices:** there is no differentiation among scenarios. Increase of prices between 2015 and 2050 for crude oil by 108%, natural gas by 82% and coal by 71%, while the price for lignite remains stable. • **Carbon prices** (in $2015 per ton)**:** would reach 72 (EMS), 188 (CS 80) and 289 (CS 95) by 2050, covered by EU energy trading system (ETS).	increase for EU28 from 9% in 2015 to 13% (CP), 16% (NP) and 19% (450ppm) by 2040. • **Technology development:** the WEO scenarios are sensitive to the assumed technological changes and cost of fuels and new technologies, including energy efficiency measures. The process of learning and cost reduction is integrated in the WEM (endogenous), both on the demand and supply side, and applies to technologies in use today, but also to future options. Cost reductions are assumed to be higher in 450ppm than in NP and CP due to higher expansion rates. Changes are differentiated by countries/regions. Assumed technology costs are discussed in the report with the focus on renewable energies and documented at least for the power sector, available as MS Excel file. • **Fuel prices:** natural gas and steam coal are differentiated by main import regions/countries and scenario. Crude oil prices are only differentiated by scenario. 450ppm has the lowest growth of fuel prices, followed by NP and CP. Crude oil prices increase from 2015 to 2040 globally by 189% (CP), 143% (NP) and 53% (450ppm). EU import prices for natural gas grow by 86 (CP), 64% (NP), 41% (450ppm) and for steam coal by 54% (CP) and 35% (NP). In 450ppm scenario, steam coal import prices for EU decrease by 11% from 2015 to 2040. • **Carbon prices** (in $2015 per ton)**:** CO_2 prices are differentiated by regions and scenarios, which would reach 40 (CP), 50 (NP) and 140 (450ppm) for Europe covering sectors of power, industry and aviation, with higher assumptions than other non-OECD countries.	power generation, direct heating and cooling applications, CHP, CCS, new nuclear power generation technologies, advanced transmission and distribution grids and smart metering, plug-in hybrid and battery electric vehicles, improvements in conventional engines, etc. The ERS reference scenario provides levelized cost development of power generation until 2050 and learning curves for demand side technologies as function of cumulative production. The EUCO policy scenarios follow more stringent ecodesign standards, but different costs assumptions are not well documented. The technology learning curves are scenario specific in the majority of the applied models. • **Fuel prices:** no differentiation by scenarios and countries, values are taken from global fossil fuel price paths assuming that the evolution of world fossil fuel prices heavily depends on climate policy aiming at limiting the consumption of fossil fuels. Increase of import prices between 2015 and 2050 for crude oil by 160%, natural gas by 98% and coal by 190%. The relatively higher growth rates are also due to the lowest historical prices (from 2010 to 2015) in the base year 2015. Compared to former reference scenario studies (EU Reference Scenario 2013), the projections for future fossil fuel import prices are around $2013/BOE 20 lower, influenced by import prices in different reference years. • **Carbon prices** (in $2015 per ton): not differentiated by country and scenario with 41 in 2030 (REF and EUCO policy scenarios) and 100 in 2050 (REF), covered by EU energy trading system (ETS). Projected carbon prices are derived from PRIMES

				modelling of the complete ETS.
	Assumptions about socio-economic development	Demographic development, GDP and gross value added growth and employment rates are the same for all three scenarios. No major shifts in socio-economic conditions described. Socio-economic background information is not further described.	Demographic development and GDP growth rates are region specific and the same for all scenarios. Scenarios are policy driven and based on techno-economic developments without major shifts in socio-economic conditions assumed.	Demographic developments are country specific. No major shifts in socio-economic conditions assumed. In contrast to the other studies private discount rates are used accounting for risks, barriers and imperfections of "optimal" developments from the society's perspective and for individual behaviors and decision making.
Applied methods and models	**Applied models and model structures, assumptions and purpose** **(e.g. forecast, or impact analysis of policies)** ***See also 'Description of analytical approaches' below for more information about the models.***	Application of nine models (soft-linked) **Scenario framework assumptions** **Fuel prices:** • not model based. Oil prices from EIA reference (EIA 2013) and statistical price correlations for crude oil, natural gas and hard coal (for continental and northwestern Europe) (Öko-Institut 2010), including a damping coefficient, form the basis for the projections. **Macroeconomic data:** • ASTRA-D: Determination of the sectoral Gross Value Added (GVA) and employment effects derived from it. • FARM-EU: economic development is modeled as gross domestic product (GDP) based on population prospects and current economic conditions. **Demographic data:** • ASTRA-D: population development based on birth, mortality and migration rates. **Resource supply** **Electricity imports:** • PowerACE: modeling of electricity in- and exports to and from Germany **Fossil fuel mining and imports:** • not considered, only fuel prices **Renewable energy potentials:** • PowerACE: GIS-based bottom-up	Application of different modules in World Energy Model (WEM) and in co-operation with one model from another institute **Scenario framework assumptions** **Fuel prices:** • calculated in WEM supply module used for international price projections of oil, natural gas and coal to stimulate sufficient investment in supply capacities to meet projected demand. Fossil fuel price paths vary across the scenarios. **Macroeconomic data:** • not model based. Economic growth assumptions for each world region based on OECD, IMF and World Bank. **Demographic data:** • not model based. Exogenous assumptions: medium-fertility variant projections from United Nations Population Division report, 2014 **Resource supply** **Electricity imports:** • not considered for modelled regions (see below) **Fossil fuel mining and imports:** • Oil supply module: to project the level of oil production in each country • Gas supply module: to project gas production and trade • Coal supply module: to assess the	Application of six models (soft-linked) **Scenario framework assumptions** **Fuel prices:** • PROMETHEUS model was used to endogenously derive consistent price trajectories for oil, natural gas and coal based on the evolution of global energy demand, resources and reserves, extraction costs and bilateral trade between regions. **Macroeconomic data:** • GEM-E3 model (a global computable general equilibrium model) was used to simulate developments of each GDP component (like investment, consumption and trade) and of the sectorial production for each Member State. **Demographic data:** • not model based. Exogenous assumptions based on European Commission: The 2015 Ageing Report **Resource supply** **Electricity imports:** • PRIMES power and steam model considers existing and future interconnection capacities in the European internal market **Fossil fuel mining and imports:** • PRIMES gas supply module considers gas

		potential analysis and integration of hourly solar and wind feed-in profiles **Energy crops, agricultural residues, etc.:** • not model based. Own calculations based on various sources (e.g. Erb, K.-H. et al. 2009 and FAOSTAT), differentiated by scenario **<u>Fuel processing and supply</u>** **Refineries:** • no model name provided: refineries and other conversion plants (e.g. biofuel production, other refining plants) are modelled independently of the power sector (on an annual basis) **Biomass and biogas provision:** • not model based. Final energy potential derived from energy crops, agric. residues, etc. (see above) **Hydrogen supply:** • PowerFlex: integrated as additional flexible load (endogenously defined) to be met in the CS 95 scenario **<u>Energy conversion, flexibility and infrastructure</u>** • ELIAS/PowerFlex: power plant decommissioning and investment model and economic dispatch (including CHP). Iterative application of investment and dispatch model. ELIAS calculates only investments in conventional power plants. Capacities of RES, storage and other flexibility options are exogenously given to the dispatch model PowerFlex. • PowerACE: capacity expansion of power plants, storage, transmission to and from Germany in hourly resolution, used for imports and exports between Germany and Europe (incl. EUMENA region) by country, provides time series data to ELIAS/PowerFlex	remaining recoverable coal resources in modelled regions **Renewable energy potentials:** • Renewables sub-module: used to evaluate long-term realizable potentials in terms of primary energy use and/or electricity generation and capacity **Energy crops, agricultural residues, etc.:** • Bioenergy supply module: used to evaluate biomass feedstock supply potentials by region **<u>Fuel processing and supply</u>** **Refineries:** • Oil refinery and trade module: used to link oil supply and demand with capacity development and utilization **Biomass and biogas provision:** • Bioenergy supply module: used to assess the ability of WEO regions to meet their demand of bioenergy for power generation and biofuels with domestic resources. It also simulates the international trade of solid biomass and biofuels. The module does not assess demand or supply related to biogas or waste. **Hydrogen supply:** • No specific modelling mentioned **<u>Energy conversion, flexibility and infrastructure</u>** • Power generation and heat plant module: used to ensure enough power generating capacity to meet demand growth, cover retirements and to maintain security of supply. Used to calculate the amount of electricity generated by each type of plant (including losses and own use) and investment associated with new generation and network infrastructure.	imports by country of origin, by transport means (LNG or pipeline) and route as well as whole sale gas prices. It studies the relationships between gas resources, gas infrastructure and the degree of competition in gas markets over the Eurasian/MENA areas and evaluates their impacts on gas prices paid by consumers in EU member states. **Renewable energy potentials:** • not model based. Derived from exogenous databases: DLR, GREN-X and several others **Energy crops, agricultural residues, etc:** • not model based. Derived from exogenous databases: EUwood, EEA, Alterra etc.) **<u>Fuel processing and supply</u>** **Refineries:** • Oil products supply model and biofuel blending: it is used to project domestic components of petroleum product prices, refining activities and refinery capacity expansion **Biomass and biogas provision:** • PRIMES biomass supply model: used to transform biomass feedstock (primary energy) into bio-energy commodities (secondary or final form) as input for the energy system such as for power plants, heating boilers or as fuel for transportation **Hydrogen supply:** • PRIMES hydrogen supply sub-model: it incorporates a large number of technologies for hydrogen production, distribution and end use **<u>Energy conversion, flexibility and infrastructure</u>** • PRIMES power/steam model: it includes

		• No modelling of heat and electricity distribution grids in Germany. **<u>Energy demand / end-use sectors</u>** • industry, residential and commercial: FORECAST: simulates energy demand for industry, trade, commerce, services, household appliances, lighting and air conditioning (for households it only accounts for appliances) • buildings: ERNSTL/EE-Lab/INVERT: forecast of building stock, envelope and heat demand with endogenous investment, dismantling and construction decisions, such as: installation of heating and water systems, renovation of buildings, total energy demand, total system costs and costs for policy programs • transport: ASTRA-D: land and water-based passenger and freight transport TEMPS: demand for air transport, and of maritime shipping and mapping of total transport demand (using results from ASTRA-D) **<u>Emissions and pollutants</u>** • TEMPS: to calculate transportation emissions and develop policy scenarios • LULUCF: derivation of greenhouse gas emissions in the field of land use, land use change and forestry • Emissions model (Öko Institut): integration of model results and their respective emissions **Other models:** • Integration model of the Öko Institut: used to integrate model results of the energy system and primary energy use	**<u>Energy demand / end-use sectors</u>** • Industry module: split into six sub-sectors to calculate energy consumption driven by the demand for specific products in energy intensive sectors • Buildings sector module: is subdivided into the residential and the services sectors and similar sub-sectors space heating, cooling, hot water, cooking, lighting, appliances to calculate final energy demand. Urbanization, population, GDP and dwelling occupancy drive the activity variables, such as appliances ownership, floor space, number of households (residential sector) and value added (services sector). • Transport module: used to estimate activity levels for each transport mode (based on end-use prices, historical trends, GDP and population development) and to project energy intensities for calculating final energy demand for each region. **<u>Emissions and pollutants</u>** • CO_2 emission module: to calculate the CO_2 emissions from fuel combustion • Non-CO_2 greenhouse gas module: to assess the amount of methane that is released into the atmosphere through venting and flaring and process-related emissions from various industrial sources by WEM region • GAINS model: to estimate local air pollutants in co-operation with the International Institute for Applied Systems Analysis (IIASA)	detailed modelling of electricity generation, trade and supply and for steam generation and distribution. The model includes chronological load curves for electricity and steam/heat distributed, 3 voltage types for the grid, interconnecting the European system in detail, network capacity and electric characteristics of interconnectors. **<u>Energy demand / end-use sectors</u>** PRIMES: core element of model framework that simulates energy demand and supply • Industrial sub-model: it consists of nine main sectors which are split in 24 different sub-sectors. Each sub-sector includes a series of industrial processes and energy uses • Residential sub-model: sub-sectors space heating, cooling, hot water, cooking, lighting, appliances. Energy demand is calculated based on assumed development of income and energy intensities driven by regulations • Tertiary sector sub-model: to project final energy demand of the services and agriculture sectors, as a function of economic activity of the sector • Transport sub-model (PRIMES-TREMOVE): produces projections of transport activity, stock turnover of transport means, technology choice, energy consumption by fuel and emissions and other externalities • CAPRI: used for activity projections in the agricultural sector **<u>Emissions and pollutants</u>** • GAINS model: used for non-CO_2 emission projections (IIASA) • GLOBIOM- G4M: used for LULUCF CO_2 emissions and removal projections

	Description of analytical approaches (e.g. top-down, or bottom-up) and methodology (e.g. optimization, simulation, accounting, economic equilibrium, game-theoretic, or agent-based)	<u>**Scenario framework assumptions**</u> **Fuel prices:** • Not model based (see above) **Macroeconomic data:** • FARM-EU: top-down global dynamic-recursive equilibrium model with myopic expectations • ASTRA-D: top-down multi-paradigm System Dynamics model using Input-Output tables **Demographic data:** • ASTRA-D: top-down multi-paradigm System Dynamics model using Input-Output tables. Unclear to what extend this methodology is used for demographic projections. <u>**Resource supply**</u> **Electricity imports:** • PowerACE: bottom-up cost optimization (expansion and dispatch) of electricity supply used for in-and exports only. **Fossil fuel mining and imports:** • Not model based (see above) **Renewable energy potentials:** • PowerACE: bottom-up GIS based assessment of renewable energy potentials **Energy crops, agricultural residues, etc.:** • Not model based (see above) <u>**Fuel processing and supply**</u> **Refineries:** • for the calculation of primary energy use, the process heat demand is considered separately. A simple projection of the required plants on the supply side takes place on the basis of exogenous assumptions. **Biomass and biogas provision:** • process heat demand and generation	<u>**Scenario framework assumptions**</u> **Fuel prices:** • Top-down economic equilibrium approach in WEM supply module calculates the output of coal, gas and oil stimulated under the given price path. If the price is not sufficient to cover the global demand, a price feedback is provided until reaching a balance between demand and supply. **Macroeconomic data:** • Not model based (see above) **Demographic data:** • Not model based (see above) <u>**Resource supply**</u> **Electricity imports:** • Power generation module: to ensure that enough electricity is generated to meet the annual demand in each region. Therefore, no electricity exchange is considered between modelled regions. **Fossil fuel mining and imports:** • Oil supply module: applied partial bottom-up approach based on field-by-field analysis from historical production by countries, standard production profiles and estimated decline rates. • Gas supply module: hybrid bottom-up/ top-down approach; Contrary to the assumed global oil market, gas is assumed to be primarily regionally traded, including trade among 17 regions constrained by existing or planned pipelines, LNG plants and long-term contracts. • Coal supply module: combination of resources approach and assessment of the development of domestic and international markets, based on the international coal price.	<u>**Scenario framework assumptions**</u> **Fuel prices:** • PROMETHEUS: a global partial equilibrium energy model that endogenously derives consistent price trajectories (see above). **Macroeconomic data:** • GEM-E3 model: a top-down macroeconomic model used for value added projections by branch of activity with recursive dynamic computable general equilibrium. **Demographic data:** • Not model based (assumptions) <u>**Resource supply**</u> **Electricity imports:** • PRIMES power and steam model: bottom-up optimization of European internal market with two options of calculation: 1) full optimization of all European countries simultaneously; 2) separate optimization per country with fixed net imports (used for scenario variants to reduce computer run time) **Fossil fuel mining and imports:** • PRIMES gas supply model: a dynamic market competition model, which covers the entire Eurasian/MENA areas and the global LNG market • Other fossil fuels: the PRIMES model database includes data on domestic fossil fuel resources by country, covering crude oil, shale oil, natural gas and solid fuels (coal and lignite). Extraction activity by country and by fuel type is projected using reduced-form equations **Renewable energy potentials:** • Not model based (see above) **Energy crops, agricultural residues, etc.:** • Not model based (see above)

		considered based on assumptions **Hydrogen supply:** • demand projection is given as input to the model (see above) **<u>Energy conversion, flexibility and infrastructure</u>** • PowerACE: Bottom-up cost optimization (expansion and dispatch) of electricity supply (imports limited to 15 % of German electricity demand in 2050 in CS 80 and CS 95). Transmission lines between Germany and neighbouring countries (EUMENA region) are expanded model-endogenously. • PowerFlex: Bottom-up cost optimization dispatch of electricity supply, CHP-plants for heat provision. Flexibility options (no expansion planning, only dispatch with perfect foresight) include: pumped storage power plants (restricted to today's installed capacities of 9.3 GW for the EMS and 15.7 GW for the CS 80 and CS 95), adjustable loads in industry (no potentials assumed in the EMS, 1.9 GW in the CS 80 and 3.8 GW in the CS 95 in 2050) and the use of electrolysis to produce hydrogen and methane (power-to-gas) (only in the CS 95). Another indirectly usable flexibility option for the electricity sector are heat storage units which offer a more flexible operation of CHP plants and the use of power-to-heat (limited to 13,500 MW in the CS 80 and to 35,315 MW in the CS 95 scenario in 2050). • ELIAS: Bottom-up simulation model for capacity expansion, retrofit, new construction, decommissioning based on the lowest full costs	**Renewable energy potentials:** • Renewables sub-module: the potential and costs for bioenergy, hydropower, photovoltaics, CSP, geothermal electricity, wind and ocean are modeled for 25 regions with dynamic cost-resource curves considering market, technical and societal constraints. **Energy crops, agricultural residues, etc.:** • Bioenergy supply module: calculates total supply potentials by region for the feedstock categories forestry products, forestry residues, agricultural residues and energy crops. **<u>Fuel processing and supply</u>** **Refineries:** • Oil refinery and trade module: a bottom-up simulation model with oil output and demand projections from WEM's fossil-fuel supply and final energy consumption modules. **Biomass and biogas provision:** • Bioenergy supply module: bottom-up optimization of energy supply to meet the demand for power and biofuels production with partial equilibrium simulation of the global trade matrix. **Hydrogen supply:** • Not available **<u>Energy conversion, flexibility and infrastructure</u>** • Power generation and heat plant module: WEM simulates investments in different conventional (including CHP) and renewable power plants based on regional long-run marginal costs (LRMCs) as decision variable. Investments in the transmission grid are a function of demand increase and of specific renewable grid integration costs. An	**<u>Fuel processing and supply</u>** **Refineries:** • Oil products supply model and biofuel blending: EU market is modelled as one stylised refinery by country involving distillation and cracking processing facilities which differ by country and are projected through endogenous investment. The model projects structural changes of refinery activities to produce least cost product mixes that satisfies the projected demand (PRIMES). **Biomass and biogas provision:** • PRIMES biomass model: economic supply model, computes the optimal use of resources and investment in biomass conversion to meet a given demand for final bioenergy products under least cost conditions. The model can be operated independently or coupled with PRIMES. **Hydrogen supply:** • PRIMES hydrogen supply sub-model: bottom-up simulation model to represent several technologies for hydrogen production from different energy carriers (coal, gas, oil, nuclear, biomass, solar, wind and electricity) **<u>Energy conversion, flexibility and infrastructure</u>** • PRIMES power and steam generation and supply model: detailed bottom-up optimization simulating energy market equilibrium in the EU and each member state in five year steps. The optimisation is intertemporal (perfect foresight) and solves simultaneously a unit commitment-dispatching problem (incl. ramping restrictions), a capacity expansion problem (investment, including storage) and a DC-linearized optimum power flow problem over

		Energy demand / end-use sectors • Industry, commercial sector and households: FORECAST-branches: bottom-up simulation modeling of electricity and heat demand • Buildings: ERNSTL/EE-Lab/INVERT: bottom-up optimization model under uncertainty from a business/actors perspective • Transport: ASTRA-D: agent-based/socio-economic model for transport sector demand (considering development of efficiency improvements and resulting fleets); choice of means of transport with logit approach coupled with top-down input-output (IO) database TEMPS: bottom-up modeling of road traffic vehicle fleet development, for the other modes of transport, the development is based on an aggregated system level modeling Not model based: agricultural and forestry, air transport as well as military transport only implicitly modeled within the GHD sector **Emissions, pollutants and other models** • Bottom-up model (LULUCF) for land-use change with an influence on available biomass potentials which are assessed top-down using secondary literature. All emissions are combined in a bottom-up accounting framework for sectorial emission calculation. **Impression on the comprehensibility of model contexts (subjective)** A graph is presented that shows how models interact at aggregated level, but interlinkages are not fully transparent. There is an iterative	hourly bottom-up dispatch optimization model provides further insights into the operation of the power systems with high share of fluctuating RES (with storage and DSM but w/o grid). Mini- and off-grid power systems are also integrated. **Energy demand / end-use sectors** • Industry module: bottom-up simulation of energy demand divided into six sub-sectors. The calculation is based on production projections and energy intensities of the manufacturing processes. Efficient technologies are adopted as a function of their payback period and estimated penetration rate, which varies by scenario. • Building module: bottom-up simulation of final energy demand of six end-uses (see above). • Transport module: bottom-up simulation of energy demand for transport modes based on activity levels and energy intensities (see above). **Emissions, pollutants and other models** • Energy related CO_2 emissions: bottom-up accounting approach for CO_2 emissions from fuel combustion calculated through multiplying energy demand by an implied CO2 content factor for coal, oil, gas differ by sector and region • Non-CO_2 greenhouse gases emissions: applied bottom-up accounting approach based on emission factors from 2006 IPCC Guidelines for National Greenhouse Gas Inventories. So far the analysis is limited to the most important sources of industrial process emissions. Methane emissions are calculated from upstream	interconnectors (allowing for AC and DC line extensions) based on trading and pricing of electricity. Heat and power is optimized simultaneously considering CHP, storages and own consumption. Hourly modelling of several typical days for each year with regard to power load, wind and solar. Load uncertainty, plant availability and variable RES considered by assumed standard deviations which influence reserve margin constraints. Decentralised generation influences grid losses and costs. Hydrogen infrastructure from hydrogen sub-model. **Energy demand / end-use sectors** • Stationary energy demand sub-models of PRIMES: for each demand sector a representative decision making agent is assumed to operate with an economic objective function. Households and passenger transport: a utility maximization function is formulated; Industrial, tertiary and freight transport: a profit maximization (or cost minimization) function is used. • Industry sub-model: bottom-up optimization considering sub-sectors and a series of industrial processes and energy uses (see above). • Residential sub-model: bottom-up optimization considering different services to households (see above). Energy consumption is related to the need for services (driven by income) and depends on efficiency and economics (relative costs and prices). Electricity demand for electric appliances is modelled by type and efficiency class. • Tertiary and agriculture sector sub-model: bottom-up optimization, demand projection as a function of economic

		modelling approach in order to reach the policy target applying the bottom up models for the energy demand but this process is not described further in the study. E.g. the linkage and iteration of the power models is only briefly described (especially for the linkage between PowerACE and ELIAS). Also the interactions between the different energy demand models are not described. An exception is the linkage of PowerFlex and TEMPS for electrified transportation (which is based on the eMobil 2050 study).	oil and gas production by WEM region. • Air pollution: bottom-up accounting approach to calculate local air pollutants of SO_2, NO_x and $PM_{2.5}$ by IIASA-GAINS model. **<u>Impression on the comprehensibility of model contexts (subjective)</u>** Interactions are realized internally (e.g. energy and water objectives). Some inputs for WEM are results from other models/modules, which are briefly described in the WEM documentation. However, model interactions and used interfaces are not described in detail and are therefore not fully transparent.	activity (exogenous) and energy prices. • PRIMES-TREMOVE transport model: detailed partial equilibrium agent-based simulation for scenario projections and impact analysis of policies. **<u>Emissions, pollutants and other models</u>** • Integrated bottom-up accounting assessment model of air pollutant and GHG emissions and their interactions **<u>Other effects</u>** • Evaluation of external impacts of agricultural and trade policies on production, income, markets, trade and the environment, from global to regional level for agricultural activity projections. **<u>Impression on the comprehensibility of model contexts (subjective)</u>** The multi-model analytical approach could only be fully understood with the help of model documentations (see Table 1 of main text). Only a graph is presented that shows how models interact at aggregated level, but without details.
	How can these models consider the future energy system (decentralized, flexible, new technologies)?	• **Centralized energy system**: assumption of a central planner • **Decentralized energy system:** decentralized technology options but no structural analysis. Use of agent-based modelling for transport sector • **Flexibility:** on the demand side by including storage (incl. e-mobility and hydrogen production) and load shifting in PowerFlex • **New technologies:** only proven RES technologies (Wind, PV, CSP) and conventional power plants (partly with CCS in the CS 95 scenario).	• **Centralized energy system:** assumption of a central planner • **Decentralized energy system:** mini- and off-grid power systems are considered • **Flexibility**: voltage and frequency control by VRE plant for generation profile shifting, flexible power plants, energy storage, demand side response • **New technologies:** are considered but no breakthroughs or fundamental innovations assumed.	• **Centralized energy system:** assumption of a central planner • **Decentralized energy system:** considers decentralized perspective due to agents in transport sector and sectorial optimization of energy supply • **Flexibility:** grid expansion planning, transport infrastructure, load shift potentials of EVs, storage, demand side technologies are considered • **New technologies:** current technologies are projected to improve in terms of unit cost and efficiency, without assuming speculative technology breakthroughs.
	Technological resolution on supply	**Power generation** (incl. cogeneration plants which were modelled separately):	**Power generation** (incl. cogeneration plants which were modelled separately):	**Power generation** (>150 cases, incl. cogeneration plants which were modelled

	side	• wind onshore • wind offshore • photovoltaics • hydropower (conventional) • biomass • biogas • vegetable oil • other renewables (geothermal, biogenic waste) • coal power plants (hard coal, lignite) • gas power plants • backup power plants • nuclear **Heat production:** • coal, oil, gas • electricity/power-to-heat • heat pumps • district heating • biomass/biogas • solar collectors **Fuel generation:** • classic conversion sector (process heat) • power-to-hydrogen • power-to-methane • power-to-liquid fuels **Infrastructure technologies:** • pumped storage	• wind (onshore and offshore) • photovoltaics (large-scale and buildings) • hydropower (large (≥10MW) and small (<10MW)) • geothermal (electricity only and CHP) • biomass (small CHP, medium CHP, electricity only PP, biogas-fired, waste-to-energy and co-fired plants) • concentrating solar power • marine (tidal and wave) • fuel cells • coal, oil and gas steam boilers with and without CCS • combined-cycle gas turbine (CCGT) with and without CCS • open-cycle gas turbine (OCGT) • integrated gasification combined cycle (IGCC) • oil and gas internal combustion • nuclear **Heat production:** • coal, oil, gas • electric boiler • heat radiator • heat pumps • 'renewables' • cooking: LPG/gas/coal, electric and biomass • insulation, retrofit, active control **Fuel generation:** • classic conversion sector (coal upgrading, refinery, gas processing and distribution, biomass processing) • power-to-hydrogen **Infrastructure technologies:** • one generic storage technology • demand side management • power and gas grid technologies • electric recharging and refueling infrastructure in transportation	separately): • wind (onshore, offshore, small scale) • photovoltaics (large-scale and rooftop) • hydropower (large and small) • geothermal (electricity only and CHP) • biomass (several) • biogas (several) • waste (several) • concentrating solar power • marine (tidal and wave) • fuel cells • coal, lignite (several) with and without CCS • oil and gas steam turbines with and without CCS • combined-cycle gas turbine (CCGT) with and without CCS • open-cycle gas turbine (OCGT) • integrated gasification combined cycle (IGCC) • oil and gas internal combustion • micro CHP • nuclear (several) **Heat production:** • direct heating coal, oil, gas • electric boiler • heat pumps • district heating (coal, oil, gas, biomass, solar, geothermal) • solar collectors **Fuel generation:** • 15 typical processes in refineries • 35 technologies for biomass conversion • 14 hydrogen production processes **Infrastructure technologies:** • power storage (pumped hydro, power-to-hydrogen, air compression, batteries) • high, medium, low voltage grids, DC/AC interconnectors, smart metering

				• district heating grid • steam distribution • gas pipelines, LNG, storages etc. • hydrogen transport and distribution • recharging and refueling infrastructure in transportation
	Model validation (parameters, formu-lation, variables), comparison with similar models/real-world data?	In the study it is not stated if the models were validated. Models are partly calibrated to statistical values (e.g. AGEB energy balances).	In the study it is not stated if the WEM model was validated. Model is calibrated to statistical values (e.g. IEA Extended energy balances).	The activity projections have been validated using typical indicators such as e.g. activity per capita. Models are partly calibrated to statistical values (e.g. energy balances, fuel prices, transport activity, forestry).
	Uncertainty treatment in the model and reporting	There are three different scenarios that show different possible developments. No other uncertainty treatment and no sensitivity analysis documented. No qualitative or quantitative reporting on uncertainties.	There are three different scenarios that show different possible developments. No other uncertainty treatment and no sensitivity analysis documented. No qualitative or quantitative reporting on uncertainties.	There are three different scenarios that show different possible developments. No other uncertainty treatment and no sensitivity analysis documented. No qualitative or quantitative reporting on uncertainties except general comments.
	Model documentation	In the study the models are shortly described with their main functions (between two and eight pages with diagrams). No further literature is named for more detailed information.	In the study, the WEM is only shortly described. The WEM documentation is available online as a separate report.	In the study the models are only shortly described. Model documentations are available online for separate model parts. Separate comprehensive PRIMES model documentations are available.
Data	**Main empirical data sources used (economic data, price data, …)**	**Main data sources/database:** no main source except AGEB energy balances for historic trends in energy sectors and normative data for energy scenarios. **Macroeconomic data and drivers:** • **Population development**: own calculation based on BMI 2013 (migration report) and census results of 2011 (Destatis 2013a) • **GDP growth projection**: taken from (Destatis 2012c) , BMVBS (2013), OECD (2012), IMF (2013), Öko-Institut et al. (2014b) • **Fuel prices**: own assumptions (for FORECAST, Powerflex) derived from EIA (2013), IEA (2013) and EC (2011, PRIMES) projections	**Main data sources/database:** mainly IEA database and energy statistics, additional external sources are mentioned. **Macroeconomic data and drivers:** • **Population development**: UN Population Division databases and own IEA analysis • **GDP growth projection:** based on IMF (International Monetary Fund World Economic Outlook 2016); World Bank databases and IEA databases and analysis. • **Fuel prices**: exogenous assumptions based on BGR (Energy Study 2015, Reserves, Resources and Availability of Energy Resources) and BP Statistical Review of World Energy 2016, World Electric Power Plants Database, Platts,	**Main data sources/database:** mainly Eurostat data for historic trends in energy sectors. **Macroeconomic data and drivers:** • **Population development:** "2015 Ageing Report" of European Commission • **GDP growth projection:** taken from DG ECFIN, European Economic Forecast of European Commission • **Fuel prices:** endogenous calculation by PROMETHEUS based on IEA, BP, BGR, USGS, EIA data **Energy demand:** • **Buildings:** updated database from the evaluation of the results from several data sources including large EU projects (e.g. ENTRANZE, ECOFYS, iNSPiRe, etc.), industrial associations (e.g. BPIE) and

		Energy demand: • **Buildings:** typology from IWU (Diefenbach & Born 2007, Diefenbach & Loga 2011); Past remediation measures are considered using one study. This data is not shown in study. • **Transport:** techno-economic parameters from project eMobil 2050 (Hacker, F. et al. 2014); traffic demand and lifetimes from TREMOD 5.25 (Ifeu 2011). Traffic demand also from (Vortisch, P. et al. 2012) • **Agriculture:** livestock, soils, economic and mineral fertilizer use (UNFCCC); Emissions (Rösemann, C. et al. 2013); Common Agriculture Policy (CAP) for base scenario (Offermann et al. 2012) • **Industry:** based on energy balances, no other data sources are documented • **Heat:** method to calculate heat demand described, three sources given as reference. **Energy Supply:** • Power supply: Power Plants Database: BNetzA-Kraftwerksliste (for ELIAS/PowerFlex) **Impression (subjective):** Many different data used for different sectors. It is often not clear which data sources are used for which information and it would therefore be necessary to collect the data, which is not very conducive to reader-friendliness and transparency.	Washington, DC. Fuel prices of the future are derived through iterative modelling. **Energy demand:** • **Buildings:** the assessment of efficiency potentials is also based on estimates available from GBPN (Global Buildings Performance Network) and CEU (Central European University) • **Transport:** Road transport: IEA Mobility Model (MoMo) plus other regional statistics, (no publication year provided) Aviation: the Assembly of the Int. Civil Aviation Organization (ICAO) *Maritime:* effect of Energy Efficiency Design Index (EEDI) introduced by the Int. Maritime Organisation (IMO) • **Industry:** Historical production from statistics: International Aluminium Institute (2015), World Steel Association (2015), METI (2014) (ethylene, propylene and aromatics), USGS (2015a) (ammonia), USGS (2015b) (cement), RISI (2012) and FAO (2014) **Energy Supply:** • capital costs, fixed O&M costs, and efficiency on WEO websites **Impression (subjective):** Some data references are provided but it remains unclear how many types of data were used in total for each sector.	research results from JRC. Further data from the household surveys of Eurostat (SECH-Survey Energy Household Consumption) was used for countries where available. • **Transport:** activity projections data from economic model (GDP, activity by sector, demographics and bilateral trade by product and by country) and also include detailed TRACCS database with up-to date information regarding the split of the vehicle fleet for each member state as input for PRIMES-TREMOVE. • **Industry:** it covers 30 industrial activities and projection data from updated and revised engineering information on process flows and corresponding technical-economic data. • **Agriculture:** split data of animal categories by five farm size classes are from Eurostat Database **Energy supply:** • Power supply: World Electric Power Plants Database, Platts, Washington, DC. (used in PRIMES) and ESAP **Impression (subjective):** Many different data used for sector analysis. It is often not clear which data sources are used for which information and it would therefore be necessary to collect the data especially in separate documents, which is not conducive to reader-friendliness and transparency.
	Data requirements (e.g. level of aggregation on demand side, temporal resolution, spatial resolution, …)	**Macroeconomics:** Germany is modelled on a national level, the study is not stating which spatial resolution the macroeconomic modeling data has and how it was used in detail **Energy demand:**	**Macroeconomics:** Data tables for 25 world regions for selected scenario years. Time Horizon of the model goes out to 2040 with annual steps in between. **Energy demand:** • **Industry:** 4 different demand drivers	**Macroeconomics:** Scenario building on EU28 member states level. Detailed sectoral value added by sectors and industrial branches. **Energy demand:** • **Industry:** covers 30 industrial activities

	(see also 'technological resolution supply side')	• **Industry:** 14 different branches with three (e.g. plastics processing) to fourteen (e.g. basic chemistry) processes, final energy demand provided for eight different fuels. Data requirements of FORECAST model are documented for all sector modules. • **Commercial:** eight different branches, 10 different categories of electricity demand. • **Transport:** pkm resp. tkm for five modes each for passenger and freight transport, vehicle stock and final energy for six different PC drive trains, final energy for freight transport for 10 different fuels; **Geographical resolution:** ASTRA-D on NUTS-2 level; TEMPS on national level. • **Households:** data requirements of bottom-up model for home appliances and heat demand is documented. Input required for a large number of building classes and allocation of different sets of technologies. **Energy supply:** • PowerACE and PowerFlex have a hourly resolution, for the other models no further information is given. **Impression (subjective):** Spatial resolution of the basic data and data processing done is often not documented. Only occasionally the study provides information on the spatial resolution of the models. Overall data requirements are partly well documented, at least qualitatively.	(end-use energy prices, population, historical production, GDP), five different branches (aluminium, iron & steel, cement, pulp & paper, chemicals) each with two to five sub-sectors and other industries (incl. commercial) representing cross-sectional technologies (motor driven equipment, process heat, steam systems, cooling/refrigeration, HVAC, lighting, electric appliances). • **Transport:** four different demand drivers (end-use energy prices, population, historical trends, GDP), two different activity variables (pkm and tkm) and five modes (road transport, aviation, rail, navigation, other). • **Buildings (households and commercial):** four different demand drivers (urbanization, population, dwelling occupancy, GDP), 4 different activity variables (floor space, number of households, appliances ownership, services value added) and nine different sub-sectors (space heating, cooling, hot water, cooking, lighting, four different appliances (refrigeration, cleaning, brown goods, other)). **Energy supply:** • more granular model of the power market with hourly resolution. (Lei: for power generation). **Impression (subjective):** Data requirements for WEM sub-models are often not provided.	and represents process flow by activity type, represents heat recovery and other horizontal energy efficiency possibilities, better linked with power/steam model regarding steam (CHP and boilers) generation for each sector of industrial activity • **Transport:** the split of vehicle fleet includes cars of conventional, hybrid, plug-in hybrid, battery electric, fuel cells, heavy good vehicles, buses, coaches, conventional and high speed rail, airplanes, ships for each member state. • **Households and buildings:** include technologies of space heating, cooling, water heating, cooking, electric appliances and lighting, thermal integrity of buildings with efficiency covered by category. **Energy supply:** • temporal resolution of scenarios: five years. Time resolution in transport and power sector modelling: typical days with hourly resolution. **Impression (subjective):** The study mentions which resolution the data has but how it was used in detail needs to be identified via additional model documents.

	Input and output data access	**Macroeconomics:** • population and GDP data as input to the models provided. Investments, changes in consumption and gross value added by economic sector, electricity price paths and percentage changes in GDP and employment were determined and are available by scenario in an ex-post assessment (not included as an input to energy system modeling/scenario framework). **Energy demand:** • primary energy demand per sector and 12 energy sources • gross electricity demand • building stock and living space house-holds, heated space commercial sector • final energy demand for households for eight different energy forms • heat demand coverage in households • heat demand coverage in industry and trade and commerce • electricity demand of households • production (tons/yr) in different branches of industry • final energy demand in industry and commercial sector for eight different energy forms • Efficiency, energy demand and modal split in transport sector **Energy supply:** • electricity generation per energy source and plant type incl. CHP (not separated) • installed capacities power generation including CHP (not separated) **Emissions:** • CO_2/GHG emissions per sector **Impression (subjective):**	**Macroeconomics:** • population and GDP development provided. No data on macroeconomic effects except investments in supply markets and end-user energy prices. **Energy demand:** • primary energy demand for seven energy sources and by region • final energy demand per sector (industry, transport and buildings) by energy form; final energy demand Others • installed capacities power generation by energy source • total primary energy demand by energy source **Energy supply:** • electricity generation by energy source and pant type • installed capacities of power generation by energy source • total oil supply **Emissions:** • total energy-related CO_2 emissions divided by coal, oil, gas • CO_2 emissions from power generation divided by coal, oil, gas **Impression (subjective):** Study presents main results for each world region. However, detailed and complete scenario/model data are not published (e.g. as supplementary material)	**Macroeconomics:** • population and GDP development provided. No data on macroeconomic effects except energy intensity indicators, price of electricity in demand sectors, total energy-related and other mitigation costs as % of GDP. **Energy demand:** • primary energy demand for 6 energy sources and by country • final energy use by fuel and sector • electricity demand by sector / subsector • final energy use by branches of industry • residential energy demand by use and fuel • final energy demand in the tertiary sector by use and fuel • passenger and freight transport activity • final energy demand in transport by mode of transport and energy source **Energy supply:** • electricity generation by energy source and plant type • RES electricity shares • Investment in new plants and refurbishment • primary energy import dependence • cost components of average electricity price **Emissions:** • carbon intensity of GDP • CO_2 emissions per sector **Impression (subjective):** Summary report presents main results and contains a relative detailed annex as in tables. Results are available by country. However, detailed and complete scenario/model data are not published (e.g. as supplementary material).

		Main results are provided in tables and diagrams. However, detailed and complete scenario/model data are not published (e.g. as supplementary material).		
	Main neglected relevant aspects and significant implicit assumptions	**Neglected relevant aspects in the modeling approach:** • no variation in macroeconomic growth across the scenarios • no variation in population development across the scenarios (strong decrease assumed only) • no in-depth sector coupling of heat and electricity in energy systems modelling • no feedback of land use change models to energy demand models • no feedback effects from energy policies, technological change and energy demand pathways to economic activity (growth) **Significant implicit assumptions:** • favourite policy conditions regarding a national integration of energy policy in Germany and regarding the European integration and goal-orientation of energy politics	**Neglected relevant aspects in the modeling approach:** • no variation in macroeconomic growth across the scenarios • no societal factors and risks considered, especially regarding CCS and nuclear technologies which are central elements of the WEO pathways • no disruptive developments considered, e.g. technology breakthroughs/innovations • no feedback effects from energy policies, technological change and energy demand pathways to economic activity (growth) in the main scenarios **Significant implicit assumptions:** • social and economic disparities between world regions persist in the long-term and result in continuing large differences between energy intensities per capita • conservative assumptions for technology developments (e.g. in terms of specific investment costs of RES) • systematic underestimation of RES development: installed capacity constantly behind historic data	**Neglected relevant aspects in the modeling approach:** • no variation in macroeconomic growth across the scenarios • no variation in population development across the scenarios which is projected to increase over coming decades up to 2050. • no societal factors and risks considered, especially regarding CCS and nuclear technologies. • no long-term target year modelled in the EUCO scenarios, therefore only incomplete consideration of the transition processes. Scenarios run the risk of lock-in effects. **Significant implicit assumptions:** • It starts from the assumption that the legally binding GHG and RES targets for 2020 will be achieved and that the policies agreed at EU and member state level until December 2014 will be implemented.
Further Aspects/subjective impressions	**Other relevant exogenous assumptions**	• **Current policies:** are assumed to be continued and all Federal States will follow the national target • **Consistency:** installed capacity of RES is given to the model-exogenously, operation is following historical load curves. Demand for the different sectors is coming from a deterministic bottom-up approach. Energy prices are taken from other studies.	• **Current policies**: assumed to be remained the same and all members will follow (but reality e. g. USA shows opposite) • **Consistency:** rather consistent and cooperative developments within world regions • **Infrastructure development:** no major limitation or barriers of infrastructure development	• **Current policies**: are assumed to be continued, rational choice is driving the developments, cooperation mechanisms achieve similar developments in all member states • **Consistency:** UNFCCC 2015 data was used for the ex-post correction of model results to ensure consistency with UNFCCC submissions; GAINS model assumptions are in consistency with

		• **Infrastructure development:** no major limitation of infrastructure development		PRIMES model assumptions on the effects of national renewable policies • **Infrastructure development:** it is assumed that for electric grids, supply follows demand and congestions in the electric grid can be removed
	Inconsistencies in the approach	• **Policy targets:** unclear how far the bottom up approach for the demand paths by sector is consistent to the economic development and the policy targets. • **Model related:** RES capacity is fixed and simulated in a separate model, the equilibrium of demand and supply is not optimized; biomass use is calculated in the demand models, not limited by the domestic biomass potential. Biomass use exceeds the potential in one scenario; due to neglected feedback loops economic and energy transition pathways might be inconsistent. • **Acceptance:** due to neglected aspects such as acceptance, investment behavior, and rebound effects, the energy transition pathways might be inconsistent regarding the societal development implicitly assumed.	• **Policy targets:** implementation of energy policies and resulting economic conditions and growth might be inconsistent as feedback loops are neglected. • **Model related:** economic development decoupled from the energy system, while energy carrier prices are determined within WEM; as exogenously assumed GDP development and calculated CO_2 emissions do not interact and this inevitably leads to the (probably inconsistent) conclusion that more policy effort leads to more decoupling of both parameters. • **Acceptance:** technology pathways may have considerable societal risks with regard to public acceptance of some infrastructural expansions, e.g., for CCS, biomass use, hydrogen technologies, large hydro, and nuclear.	• **Policy targets:** RES are reached but only legally binding regulations are included and rather conservative technology learning assumed. • **Model related:** perfect foresight is applied regarding the Energy trading system (ETS) pricing, but in general limited foresight in final demand sectors. This is plausible only if explicit measures are applied to make the ETS price transparent and reliable (this, however, may contradict the market based cap and trade approach). • **Acceptance:** forestry is assumed to be at maximum sustainable level. Yet a further increase is assumed to be possible if economically feasible that may be not in line with national and EU law. Also public acceptance of decisions implicitly made in the scenarios is neglected.
	Inconsistencies of input data	• oil price is the same for all future scenarios no matter which share of renewable is reached. If other countries have a similar development this will influence the oil price because demand for oil will decrease. • population decrease and GDP growth does not interact.	• investment cost projection of renewable energy technologies remains rather conservative in all scenarios while global market development is far higher in the 450ppm scenario. • constantly very low coal investment costs in China (probably because of low air pollution standards) is inconsistent in a world of new policies and ambitious climate change targets. • GDP in Africa remains low but population growth is high, therefore GDP and energy	• ‘yet unknown policies’ are assumed to reach the RES share targets, this raises concerns about how these policies fit to other assumptions. • while ETS targets are assumed to be achieved on EU level (i.e. not necessarily member state level), RES share targets are assumed to be met on member state level (“very limited recourse to cooperation” among member states). While it is made clear that this bases on communication with the member states,

			use per capita remains at a very low level.	it might be an inconsistent assumption.

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