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How to assess the quality and transparency of energy scenarios: Results of a case study

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ABSTRACT

The exploration and evaluation of strategies for decarbonizing the energy system is the subject of a series of national and international studies conducted by governmental, industrial and independent stakeholders. These studies play an important role in the energy policy debate on understanding and assessing different transformation paths of the energy system, technology options and their implications. They support strategic decisions on the type and scale of investments in the energy system under uncertain future conditions. However, in recent years the increasing complexity of these studies lead to a decreasing transparency even though their transparency and traceability is important for society, politics, research, and industry.

In this article, three energy scenarios at different regional scales are reviewed according to their compliance with our pre-defined criteria of transparency. They are analysed in detail with regard to their objectives, methods, data used, results obtained and traceability. Our comparison shows that the results are often presented sufficiently in order to inform decision makers. However, the underlying model-based methods lack information on data exchange between the models, the transparent description of model couplings and a discussion on the rationality of method selection and the strengths and weaknesses of the applied approaches. Based on our findings, we present some general advice for energy scenario developers on how to ensure transparency and traceability in future energy scenario studies.

1. Introduction

During the last decades, the complexity of energy system modelling and scenario studies regarding the energy transition increased significantly. While most scenario studies during the 1990's and in the beginning of the 2000s used bottom-up models on a national and annual scale and focused on the potentials and fundamental role of renewable energy sources (RES; e.g. the analysis of the German energy system in Ref. [1]), current scenario studies are more international and on a higher level with respect to the technological, temporal, as well as regional detail. Furthermore, they also consider interactions between the power, heat/gas, and transport sectors (sector coupling) by applying several interlinked, sophisticated models to derive further insights into the 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 much attention by the media, public, and politicians [2–4]. Ideally, published information originates from scenario studies that focus on a broad range of possible conditions and available options and provide transparent and robust results and conclusions. Such studies must have a holistic view and integrate substantial state-of-the-art background knowledge such as information 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

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Abbreviations: CPS, Climate Protection Scenario 2050; ERS, EU Reference Scenario; REF, reference scenario; WEO, World Energy Outlook; EMS, Existing Measures Scenario; CP, Current Policies Scenario; NP, New Policies Scenario; CS 80, Climate Protection Scenario with 80% GHG reduction; CS 95, Climate Protection Scenario with 95% GHG reduction; EEG, Renewable Energy Sources Act; WEM, World Energy Model; EU-ETS, European Union Emissions Trading System; ESD, Effort Sharing Decision; PRIMES, Price-Induced Market Equilibrium System; EUMENA, Europe, Middle East and North Africa; NP, not provided; LRMC, long-run marginal costs; ESMs, energy system models; LULUCF, land use, land use change and forestry

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energy data are necessary to generate plausible and comparable results.

In the scientific, political, and industrial context, scenario data are used as an orientation framework or even for model parametrisation in scientific analyses 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 those in models. Therefore, model-based scenario building often leads to results that are not fully transparent and understandable for scientists, stakeholders, and other interested individuals. This lack of transparency can give rise to the assumption of deliberate manipulation 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), based on which the role of fossil fuels is substantiated and the dynamics of the RES progress are repressed, which seems to be consistent with the interests of IEA member countries [6,28].

In addition, the use of complex models or even model coupling is associated with a large number of uncertain and influencing assumptions regarding their parametrisation such that their overall quality and consistency are unclear [7,34,35]. To grasp the complexity of models with regard to the applicability of various modelling techniques, Börjeson et al. [8,9] presented classifications of energy system models (ESMs) and scenario 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] and Nursimulu [11] emphasised that a complete understanding of scenario analysis and its results can only be achieved through the greatest possible transparency and comprehensibility of the applied data and models despite the classification of the models. One recent study by Cao et al. [29] provided modelers with a fully operational transparency checklist focusing on scenario studies that examine energy systems. Hülk et al. [12] already applied this transparency checklist methodology to evaluate the degree of transparency of their own modelling work. In addition to many other researchers (e.g. Refs. [36,38]), they derived 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. [30] revealed that the main challenges regarding open energy modelling frameworks are the complexity, scientific standards, utilisation, interdisciplinary modelling, and uncertainty. A high scientific standard of the models as tool for scenario building does not guarantee that robust statements are made. Instead, the approaches must be comprehensively evaluated, from the narratives and assumptions, data sources, and model approaches to the data evaluations and derivation of conclusions.

The extent to which scenario analyses can be evaluated based on published scenario studies is the subject of this article. In the following analysis, we systematically examine three exemplary scenario studies that result from the application of complex models and the use, exchange, and generation of a wide variety of data regarding their transparency and comprehensibility. The studies are systematically described according to various criteria suitable for model and scenario evaluation presented in the scientific literature. The points raised are essential for the understanding of scenario analyses and should be comprehensively addressed and presented in future scenario studies. This article has the following structure. We describe our methods in Chapter 2 and provide and discuss our results by comparing the most important assumptions and applied models in Chapter 3. The implications and recommendations for scenario developers and our final conclusions are provided in Chapters 4 and 5, respectively.

2. Methodology and concept

We focus our analysis on the Climate Protection Scenario 2050 (CPS) [23] for Germany, European Union (EU) Reference Scenario (ERS) [13] for Europe, and World Energy Outlook (WEO) [21] for the world and its modelled regions. All three scenario studies represent important and current quantitative bases for guidance regarding energy politics as well as investment decisions of businesses and discussions in the society. These studies are currently the most relevant published scenarios for the corresponding geographical areas, which were developed using advanced modelling approaches. The overlapping geographical scopes of the three selected studies make it possible to compare the model-based scenario results. However, because this analysis is limited to the three scenarios, which each have a different geographical focus, the statements made in this article cannot be generalised but are intended to demonstrate how modelers can assess the presentation of their work. In addition, we advise interested individuals on how they can evaluate the studies presented to them in terms of the transparency criteria and traceability. Furthermore, the selection of a limited number of studies and the documentation of the results in a comprehensive table enable the reader to follow the points criticised here for each of the reports. This would not be possible if many scenario studies would be included, because of the high documentation effort, and is beyond the scope of this case study.

Each of the selected scenarios is conducted at a different regional level: 1) at the national level: the CPS for the energy transition in Germany, 2) at the supranational level: the ERS for the energy future in Europe, and 3) at the global level: the WEO for long-term scenarios according to different world regions. We outline their differences with a special focus on the traceability of the model approaches and model linkages and the ability to understand and access input and output data. We only use publicly available information such as the main study and study-related supplementary documents because we require study

Table 1
Sources included in this assessment.

Scenario study	Information gathered	Source	Comments
ERS '16	Main study	[13]	The main study report only provides results in the main text and supplementary sheets. Study-specific supplementary model documents are available online. However, additional efforts are needed to interpret the model input and output and model linkages related to the supported scenario analysis.
	Supplementary, on the energy system	[14]	
	Supplementary, on transport	[15]	
	Supplementary, on biomass	[16]	
	Supplementary, on the air pollution and climate change simulation tool	[17]	
	Supplementary, on the computable general equilibrium model used for value-added projections by branch of activity	[18]	
	Supplementary, on the global forest model	[19]	
	Supplementary, on agricultural activity projections	[20]	
IEA WEO '16	Main study	[21]	The main study includes the objective and results, while the supplementary information contains the description of the model and data sources.
	Supplementary, on the methodological description	[22]	
CPS '15	Main study	[23]	The main study provides the results and background information about the models and the model linkages. There are no further study-specific supplements.

Table 2
List of the analysed categories for each of the three studies.

Category	Analysis points, collected for each study
Scope & purpose of the 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 socioeconomic development
Data	Main empirical data sources used (e.g. economic data, price data) Data requirements (e.g. level of aggregation on the demand side, temporal resolution, spatial resolution) Input and output data access Main neglected relevant aspects and significant implicit assumptions
Applied methods & models	Applied models and purpose (e.g. forecast or impact analysis of policies) Model structure (internal and external assumptions of the model) Analytical approach and methodology (e.g. top-down/bottom-up; optimisation, 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 the supply side Model validation Uncertainty treatment in the model and reporting Model documentation
Further aspects	Other relevant exogenous assumptions Inconsistencies in the approach Inconsistencies of the input data

authors to 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, the analysis of cited secondary literature (such as peer-reviewed papers as well as grey literature) is beyond the scope of this study.

Our analysis contains the following main methodological steps:

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

Table 2 shows the selection of the categories used as evaluation criteria, which is mainly based on [29]. The main categories are basic information about 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 of the studies. While Cao et al. [29] take the perspective of the modeler and formulate a systematic manual for transparent documentation, we also look for information that allows the greatest possible understanding of the work that was carried out, the data used, and the results obtained. Hence, in addition to the checklist from Cao et al. [29], we use the model classification method from Van Beeck et al. [24] and our own considerations to define a list of categories that is well suited to analyse the studies from an external perspective. This first step in our analysis was necessary to adapt the categories to the information available from scenario reports and documentation.

Detailed results of the systematic and comparative analysis for all three studies are provided in the Supplementary material. The comparison is presented in a structured table including a description of the data structures, the analytical approach, methods used, and comments on how the studies cope with our evaluation criteria. The main aspects according to the four evaluation categories are further discussed in Chapter 3. In addition, we provide a concise graphical overview (Fig. 2) that shows the typical structure of scenario analyses including the analysed sectors and components and the underlying model types and accessibility of input–output data.

3. Scenario characterisation and discussion

In this section, we discuss the evaluation results according to the criteria defined in Table 2 (for further details regarding the results, see the tables in the Excel data sheets provided as Supplementary material). In the following sections, we will discuss the most important aspects for which we gained interesting insights.

3.1. Scope and purpose of the analysis

As indicated in Table 2, the category 'scope and purpose of the analysis' is measured by seven evaluation criteria. In the three studies, the background information about the authors, participating institutions, aims and funding of the studies, geographical scope, and time horizons is described in a comprehensible way. The German and European studies were each funded by governmental institutions, while the IEA and its studies are generally funded by the Organisation for Economic Co-operation and Development (OECD) member states. The aims of the studies are very similar and clearly defined: 1) to inform policy makers where current policies and policy ambitions may lead the energy sector, and 2) which policies and measures are needed to achieve specific climate targets. Naturally, the WEO addresses the global objectives of controlling global warming (in the case of < 2 °C above preindustrial levels), while the other two reports 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 German study is carried out until 2050, while the WEO analyses the transformation paths until 2040. Among the seven scenarios in the ERS, only the reference scenario (REF) has a time horizon until 2050, while all other six policy scenarios only cover the period until 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 (e.g. the < 2 °C target). The CPS and WEO explicitly examine explorative scenarios, whereby the Existing Measures Scenario (EMS) for Germany corresponds to the current policies scenario (CP) of 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 will 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 based on 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, and EUCO3030), respectively, using greenhouse gas reduction targets, efficiency measures, and share of RES in the gross final energy consumption or other specific targets for RES deployment in the 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.

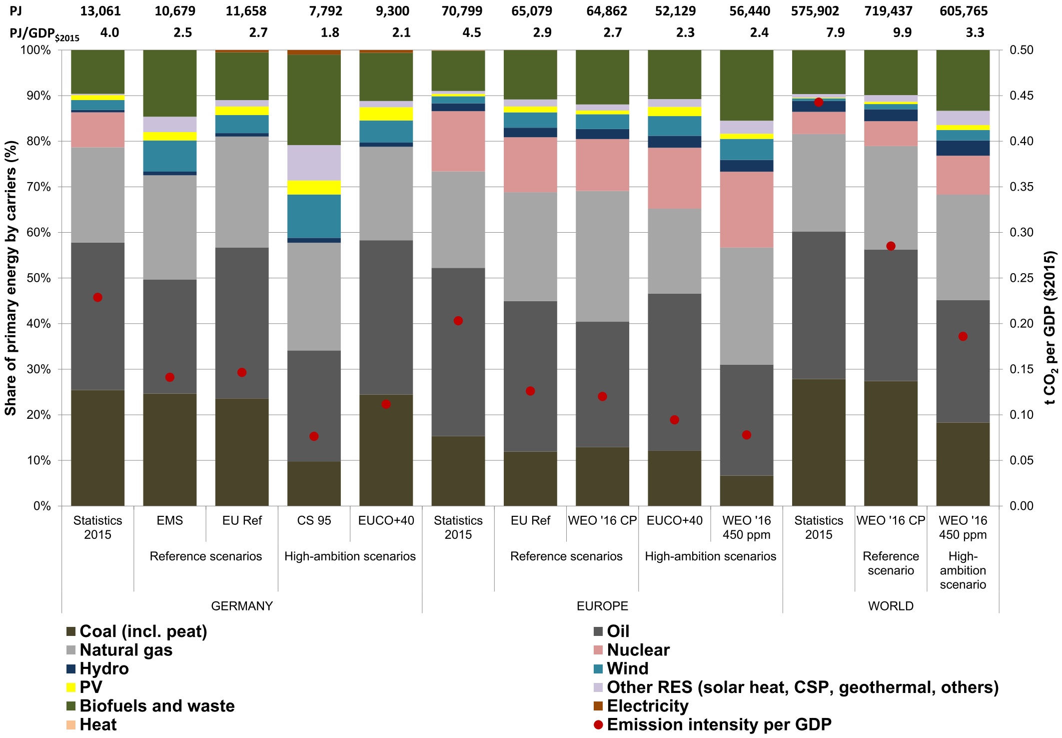


Fig. 1. Primary energy demand by energy type and energy-related CO_2 intensity in the reviewed energy scenario studies for the year 2030 differentiated by baseline scenarios and most ambitious scenarios for Germany, Europe, and the world. For the ERS and CPS, the category 'Solar' in the datasheets of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

3.2. Results and traceability of the main assumptions

In general, assumptions and/or modelling results on region-specific population development and economic growth coupled with assumptions and/or modelling results on efficiency improvements represent the main drivers of the demand development in scenario analysis and may have a great influence on the supply structure and potential depth of sector coupling. Thus, in this section we focus on the main quantifiable assumptions and characteristics of the three studies, such as economic and population trends, energy demand, differences in electricity generation (i.e. share of RES, fossil fuels, nuclear power, and biomass), technological development, fuel and CO_2 prices and point to transparencies regarding these assumptions, which would require more comprehensive clarification in the scenario studies to be understandable to the reader.

3.2.1. Key differences of the scenario results

To understand the degree of ambition of the scenarios and to identify the most important energy sources and technologies, we present the structure of the primary energy supply and CO_2 emissions per GDP in 2030 (Fig. 1). The overlapping geographical analysis frameworks of the studies allow for a comparison of the CPS and ERS for Germany and the ERS and WEO for the EU28 scenario. The selection of the year 2030 is due to the limited analysis horizon of the ERS scenarios. Thus, the figure indicates the mid-term transformation perspectives of different scenarios. For each overlapping geographical area, we present the reference and most ambitious scenarios in terms of emission reduction and additionally compare the values (also for the world average in the WEO) with the 2015 statistics from Ref. [25].

The comparison shows that the studies significantly differ in the reference and most ambitious scenarios regarding their primary energy supply structures and CO_2 efficiencies per GDP. When comparing the CPS and ERS scenarios for Germany, the latter study shows fundamentally lower renewable shares. However, the ERS REF and all scenarios for Germany derived in the European study do not consider 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. It remains unclear whether the German national goal was deliberately not considered or ignored. A comparison of the EU28 scenarios based on the ERS and WEO shows a higher use of natural gas in the reference scenario of the global study. With respect to the ambitious scenarios, the WEO shows a higher use of renewable energy, especially biomass, but also nuclear power.

3.2.2. GDP and population development

All studies assume the same population development and GDP growth in their reference and transformation scenarios. For Germany, the CPS and ERS expect a GDP growth of 50.5% and 61.5%, respectively, with population expectations ranging from −10.0% and −9.3% from 2015 to 2050. The ERS and WEO expect the GDP for the EU28 scenario to increase by 65.4% and 71.2%, respectively, between 2015 and 2040. The population of the EU28 is assumed to slightly grow by 2.5% (ERS) and 0.6% (WEO) from 2015 to 2040. The WEO estimates a global GDP and population growth of ~150% and ~25%, respectively, between 2015 and 2040. The main reasons for the high global GDP growth compared with 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 the differences between the studies are small. The assumptions behind these two drivers are provided to the reader in a clear and understandable way.

3.2.3. Differences in the electricity generation with a focus on the roles of carbon capture and storage and nuclear energy

The future electricity demand per GDP for the same regions differs in the individual scenarios (depending on the degree of ambition) of the studies as well as between the studies themselves. This is mainly due to different (regionally specific) assumptions about energy efficiency policy, efficiency development and electrification rates in the sectors heat, transport and industry in the scenario studies (and respective scenarios). It is noticeable that only the EUCO + 40 and EUCO3030 scenarios for Germany are in line with the 50% target (share of electricity produced from renewable energy sources in the gross electricity consumption) set by the German Energy Concept. However, it remains unclear why the target is violated in the other scenarios of the ERS.

Regarding the role of the much-discussed carbon capture and storage (CCS) technology in the CPS, it would only be used in the CS 95 scenario for industry and biomass combustion starting in 2030. The capture rate is assumed to be far below 50 Mt CO_2/yr in all scenario years of the CS 95 (~6% of the German CO_2 emissions in 2015). Based on the ERS, fossil fuel combustion with CCS would be implemented in the EU28 in 2020 but not in Germany. The installed capacity equipped with CCS for the energy conversion of solid fossil fuels would reach up to 17 GW (66% of the solid fuel based generation and ~3.4% of the total generation capacity) by 2050 for the EU28. In contrast to the targets for renewable energies with respect to electricity generation, the ERS study is corresponds to the current legislation in Germany but does not justify the assumed installation rates of CCS technology in Europe. In the WEO 450 ppm scenario, CCS would start to play a relevant role in 2025 because 4% of the global power plants are equipped with CCS technology and 60% of them are coal-fired. In the 450 ppm scenario, the share of coal power plants would only account for 7% of the total installed capacity in 2040, while 70% of them would be fitted with CCS technology (260 GW, mostly in China and the United States) globally. The possible effects associated with CCS, such as large CO_2 leakages and social barriers (see e.g. Wennersten et al. [26] for the characterisation of the various types of risks), are quantitatively included in the ERS via risk premiums (i.e. the technology becomes more expensive). The CPS qualitatively refers to the risk of CO_2 leakages, while the WEO only refers to the intensive water use of the technology and assumes that it can be installed in regions in which the technology is politically accepted.

Nuclear power would start to phase out in Germany in 2025, while the share of nuclear power in the installed power capacity would reach 7% by 2050 in the EU28. In the WEO, a renaissance of nuclear energy occurs in all scenarios with shares of 9% (CP), 12% (NP), and 18% (450 ppm) in the global power generation, while fluctuating RES only play a minor role. Thus, the WEO assumes that nuclear energy will play an increasingly important role and will be socially accepted by the public in the future. This seems to be highly questionable regarding recent acceptance surveys about nuclear power (see e.g. Siegrist and Visschers [27]). The ERS and WEO deal with nuclear power in similar ways to CCS technology (risk premiums in the ERS, qualitative discussion of water consumption, as well as installation where politically accepted in the WEO).

3.2.4. Development of fuel and CO_2 prices

The 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, no differentiation is made among the scenarios and the prices increase between 2015 and 2050. The ERS also does not differentiate between scenarios and EU28 countries. In contrast to the former two studies, the prices of natural gas and steam coal are differentiated in the WEO by regions and scenarios for the main import regions or countries. The prices of crude oil are only differentiated by scenarios because of the existence of a global market. The 450 ppm scenario has the lowest expectations with respect to the growth of future fossil fuel prices, followed by the NP and CP scenarios. Thus, it can be stated that only the WEO incorporates the interdependencies between fossil raw material prices and scenarios. This may be justified based on the fact that the pure price taker approach does not apply to a global analysis (e.g. an analysis for Germany in the CPS). On the other hand, at least for Europe, it could be expected that the scenarios aimed at a high CO_2 reduction will have an influence on global market prices (see e.g. Zhang and Sun [50]). Such interactions or uncertainty analyses based on sensitivity estimates are not considered in the CPS or ERS and might substantially influence the results (e.g. the choice between hydrogen and fossil fuels in industrial processes and potentially induced necessary reduction measures in other sectors in both normative and explorative scenarios).

Other influential policy variations among the scenarios are the scope and level of carbon pricing, which have a major impact on the relative costs of the use of different fuels. In general, surcharges on the fossil fuel prices have a strong incentive effect on emission reductions, which must be addressed when developing climate protection strategies. While the CO_2 prices are differentiated between the scenarios in the CPS and WEO (also by regions in the WEO), the carbon prices among the scenarios are not differentiated in the ERS (at least, they are not reported). The ERS scenarios only focus on the policies for efficiency improvement, GHG emission reduction, and RES share increase without discussing the influence of higher carbon prices (although the Price-Induced Market Equilibrium System, PRIMES, simulates emission reductions in the European Union Emissions Trading System, EU-ETS, sectors as a response to current and future EU-ETS prices). Even in the most ambitious EUCO + 40 scenario, the energy-related CO_2 emissions in 2030 (2132 t) do not nearly match those of the WEO 450 ppm scenario (1844 t), which targets a global temperature increase of $< 2\,^{\circ}C$. Thus scenarios that only have a short-to medium-term perspective, such as the ERS, carry the risk that they will not be consistent with the global long-term climate goals or will discard the potentially higher regional transition costs after 2030.

3.2.5. 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). The documentation of the assumed technological progress and the consideration of new technologies in the individual models used in the CPS widely vary but do not allow for a comprehensive technology description. In the transformation sector (heat and power generation), new technologies that are currently not mature enough for the market are not included in the study. Learning curves are provided as input to all models of the transformation sector, but no further information on decreasing costs and/or increasing efficiencies is given. It can therefore only be assumed that potential efficiency gains and decreasing technology prices are included as assumptions in all models, but no feedback loops regarding the installation rates and cost effects are incorporated in the analysis. However, this limitation seems to be acceptable for a study focusing on Germany because the influence on the market prices of globally traded energy generation technologies (e.g. PV) may be marginal. Feedback loops are more important for technologies that are subject to high local value creation such as wind turbines. 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 more explicitly describes the penetration and choice of new technologies considered in the PRIMES model. In contrast to the CPS, the ERS REF also provides the levelised cost of electricity (LCOE) development of the power generation both of RES and non-RES technologies until 2050 and learning curves for demand-side technologies, which reflect the decreasing costs and increasing performances as a function of the cumulative production. The EUCO policy scenarios follow more stringent ecodesign standards, but different cost assumptions for technologies are not well documented. Technology learning curves are scenario-specific in most of the applied models in the ERS but only documented for the REF scenario. Similarly, the process of learning and cost reduction for the WEO scenarios is fully incorporated in the World Energy Model (WEM), both on the demand and supply sides, and applies to technologies in use today and those approaching commercialisation. The 450 ppm scenario assumes a higher cost reduction than the NP and CP scenarios because it is assumed that the more a technology is used, the faster is the cost reduction. This is also differentiated by country/region.

In conclusion, it can be argued that the influence of the scenario specific expansion of technologies on the techno-economic parameters is not explicitly modelled (technology price as a function of deployment) in the three studies but is taken into account in the scenarios via exogenous, scenario-specific assumptions in the ERS and WEO. In contrast, the same technology cost parameters are assumed in all scenarios of the CPS. The implications of such assumptions should be better highlighted in future studies because they may have a significant impact on the development (especially in cost optimisation models) of technology portfolios and the resulting policy advice.

3.3. *Applied methods and models*

In the following sections, the core methodological aspects of the three scenario studies are compared using the table provided in the Supplementary material in combination with specific findings about the applied models and the transparency of the provided input and output data. All three studies follow an advanced scenario building approach but differ in many aspects. However, it remains difficult to assess the methodological robustness of the three studies because of the limited transparency regarding the applied models and model coupling and associated input–output data.

3.3.1. *Analytical approach and methodology*

We systematically characterise the traceability of the studies and their analytical approaches with respect to framework assumptions, resource supply, fuel processing and supply, energy conversion, network and flexibility options, end-use sectors, and emissions and pollutants. Using this representation of model-based scenario analysis, we graphically capture the main components regarding the applied methodology (e.g. top-down or bottom-up approaches) and the transparency and presentation of the input and output data (input data: database, statistics, or literature; output data: results of general calculations/data processing of the applied models). To represent the complexity of the scenario studies in a well-structured figure, we define several acronyms with clear rules for the classification of the model parts:

Assessment methods

- We mark aspects of the studies as not available (**N/A**) if the study mentions certain components of the modelling framework and considers them in the analysis; based on this, the modelling/underlying assumptions of the analysis are insufficiently described (e.g. only mentions them qualitatively).
- We mark modules of the study as available (**A**) when the input data are 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 the different scope of a study) is marked with '/'.

Data

- We highlight the 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 Fig. 2).
- The clear naming and representation of output data/processed data are marked as well illustrated output (**O**); otherwise, we define it to be **NP** (see Fig. 2).

Note that the resulting figure does not describe internal model links (e.g. between different models in studies with model coupling).

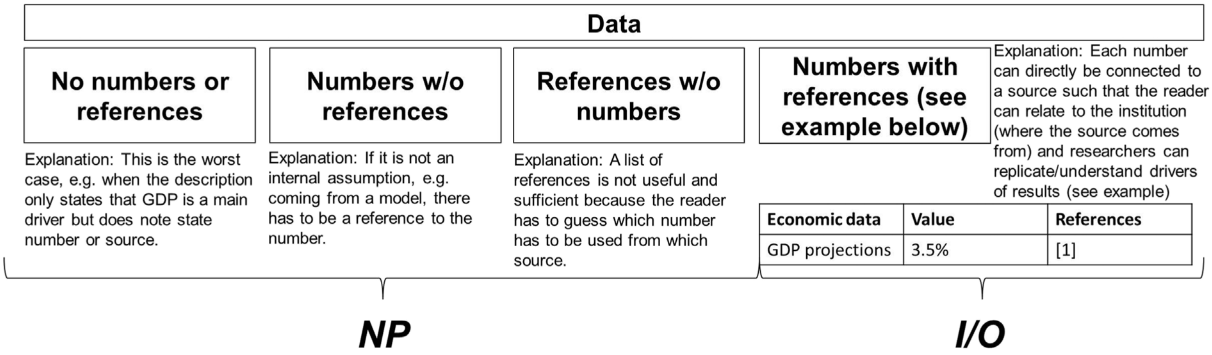
Fig. 3 presents our evaluation results in a condensed format (more information regarding technological resolutions and model structures can be found in the Supplementary material). The following sections provide an in-depth discussion of significant methodological aspects of the scenario construction in the three studies.

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 citing further literature for more detailed information, while the ERS and WEO include comprehensive model reports and documentation online, for example, for the PRIMES and WEM models, respectively (see Table 1).

General framework assumptions, such as normative objectives, are usually not based on model results but are derived from other studies and official policy objectives or are defined within the consortium. Quantitative scenario drivers, such as fuel prices and macroeconomic and demographic development, are either determined by assumptions or model-based calculations. The development of fuel prices in the CPS is taken from other studies, while it is calculated using models in the ERS and WEO. 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 the 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 the demand and supply take place until the equilibrium is attained. In the CPS and ERS, macroeconomic data (sectoral developments aggregated to the GDP) are derived based on top-down equilibrium models, while the WEO uses assumptions for the GDP development based on forecasts from International Monetary Fund (IMF), World Bank, and IEA databases and analyses. In addition, 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 WEO use assumptions derived from secondary literature for this scenario driver. In general, the use of models to quantify the scenario drivers within the consortium may enable potential model interactions between the scenario analysis framework and price sensitive models, which in principle can improve the 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 considered in any of the studies of the macroeconomic and demographic developments (the CPS only carries out an ex-post assessment of the scenarios regarding these variables). An exception regarding the commodity prices is the WEO, which assumes scenario-dependent price paths.

Electricity as a resource in an imported form is only relevant for analyses of limited geographical areas (as it is only the case in the CPS). In the CPS, these are calculated using an additional supranational bottom-up optimisation model for Europe, the Middle East, and North Africa (EUMENA). The ERS applies bottom-up optimisation models to study the internal electricity market of the EU (no electricity exchange with countries/regions outside the EU28), while the power generation module in the WEO ensures that enough electricity is generated to meet the annual demand volume in each region (thus, no electricity exchange is considered for each modelled region). While the fossil fuel mining and import are not modelled in the CPS (Germany as a price taker), the ERS uses a gas supply module, which calculates the gas import by country of origin, transport means (liquefied natural gas (LNG) or pipeline), and route as well as the wholesale gas prices for the EU member states. However, the WEO contains detailed modules for oil and gas to project the levels of production and trade and a module for coal to assess the remaining recoverable resources in the modelled regions. Renewable energy potentials for wind and PV plants are calculated bottom-up in the CPS using a geographical information system



Explanation: This is the worst case, e.g. when the description only states that GDP is a main driver but does note state number or source.

Explanation: If it is not an internal assumption, e.g. coming from a model, there has to be a reference to the number.

Explanation: A list of references is not useful and sufficient because the reader has to guess which number has to be used from which source.

Explanation: Each number can directly be connected to a source such that the reader can relate to the institution (where the source comes from) and researchers can replicate/understand drivers of results (see example)

Economic data	Value	References
GDP projections	3.5%	[1]

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

(GIS). However, these renewable potentials with the corresponding feed-in profiles only appear to be taken into account in the supranational model for electricity import and export modelling. In the ERS, the renewable potentials are based on various sources, while the WEO has a submodule for RES to calculate dynamic cost-potential curves including technological learning for electricity supply from RES (such as bioenergy; hydropower; PV; concentrated solar power, CSP; geothermal electricity; wind; and marine energy). The use of energy crops and agricultural residues is not modelled in the CPS and ERS but is based on various other sources and databases providing constraints on potentials and certain sectoral allocation methods (e.g. by defining market shares). In contrast, the WEO uses a bioenergy supply module which enables the calculation of the biomass feedstock supply by region. Therefore, the modelling of fossil primary energy carriers is only conducted if, for example, the individual regions also have a potential influence on the global demand and prices. The smaller the geographical area is, the smaller is the potential effect 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 of the models is, the higher are the potential exchange of electricity between regions and the associated need to model these energy flows.

The fuel processing and supply and refineries and other conversion plants (e.g. biofuel production, other refining plants) are modelled independently in the power generation sector on an annual basis in the CPS. However, the modelling 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 the domestic components of the petroleum prices, refining activities, and refinery capacity expansion. The biomass and biogas provision are not based on a model in the CPS but derived from the potential of energy crops and agricultural residues. In the ERS, a biomass model is used to transform the biomass feedstock (primary energy) into bioenergy commodities (secondary or final form) used as input for the energy system (e.g. 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 enables the international trade of solid biomass and biofuels between world regions. Such modelling of the international trade of biomass and biofuels is not considered in the CPS and ERS.

The hydrogen production and other process chains (such as methanation) are modelled in the CPS using the pure increase in the electricity demand, whereas a hydrogen supply submodel is used in the ERS to incorporate many technologies for the hydrogen production, storage, distribution, and end use. The inclusion of infrastructure costs in the large-scale use of hydrogen (or derivatives) in the transport, industry, and power generation sectors can significantly influence the model results. In the WEO, the production of hydrogen is not specifically considered and modelled.

Regarding the energy conversion, flexibility, and infrastructure, a model group of three models is used in the CPS; one is used for the import and export modelling of electricity between Germany and the EUMENA region in which the potential expansions of the grid transfer capacity and energy storage are also considered. The expansion and operation of power plants and the flexibility in Germany are separately modelled; one model simulates the expansion of the power plants and another model optimises the economic dispatch in hourly resolution (including combined heat and power (CHP) plants), whereby the flexibility options (such as flexible hydrogen production and storage systems) are also mapped (the capacities are exogenously given). However, the grid infrastructure of Germany is not modelled (Germany is modelled as a ‘copper plate’). The ERS uses a bottom-up optimisation of the energy supply that simulates the energy market equilibrium in the EU and each of its member states in five-year steps with a sectorial optimisation for the heat and power sectors. The model calculates the infrastructural needs in terms of electricity transmission and distribution grids, heat/steam distribution grids, and energy storage systems including hydrogen generation. The power and steam/heat markets are simultaneously simulated to capture trade-offs between cogeneration/CHP and condensing power plants and between the self-production and distribution of steam/heat. The transmission grid is modelled as entire system of interconnectors in Europe and as Alternating Current (AC) and Direct Current (DC) line extension including optional remote connections with offshore wind power in the North Sea and with North Africa and the Middle East. Highly distributed generation at consumer premises is also included and is considered when calculating the 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 the demand is calculated with a simulation model, which uses the regional long-run marginal costs (LRMCs) as a decision variable for investments in conventional (including CHP) and renewable power plants. Investments into the transmission grid are a function of the demand increase and additional transmission network costs are derived from 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 storage and demand-side management (DSM) measures but excludes the expansion of power grids within the regions. Mini- and off-grid power systems are also integrated into the WEM model by choosing available technologies based on their regional long-run marginal costs.

It can be inferred that the electricity transmission grids and energy storage systems are all modelled in the studies as methodological extension of scenario analysis. However, the modelling of the electricity grid and the generation of results and analytical statements clearly differ. While the CPS does not model the grid congestion and related costs within Germany, the costs for grids are integrated in the WEO using a heuristic approach. In addition, there is no cost-optimal network expansion. On the other hand, the grid expansion of the network infrastructure between the individual countries is cost-optimal in the

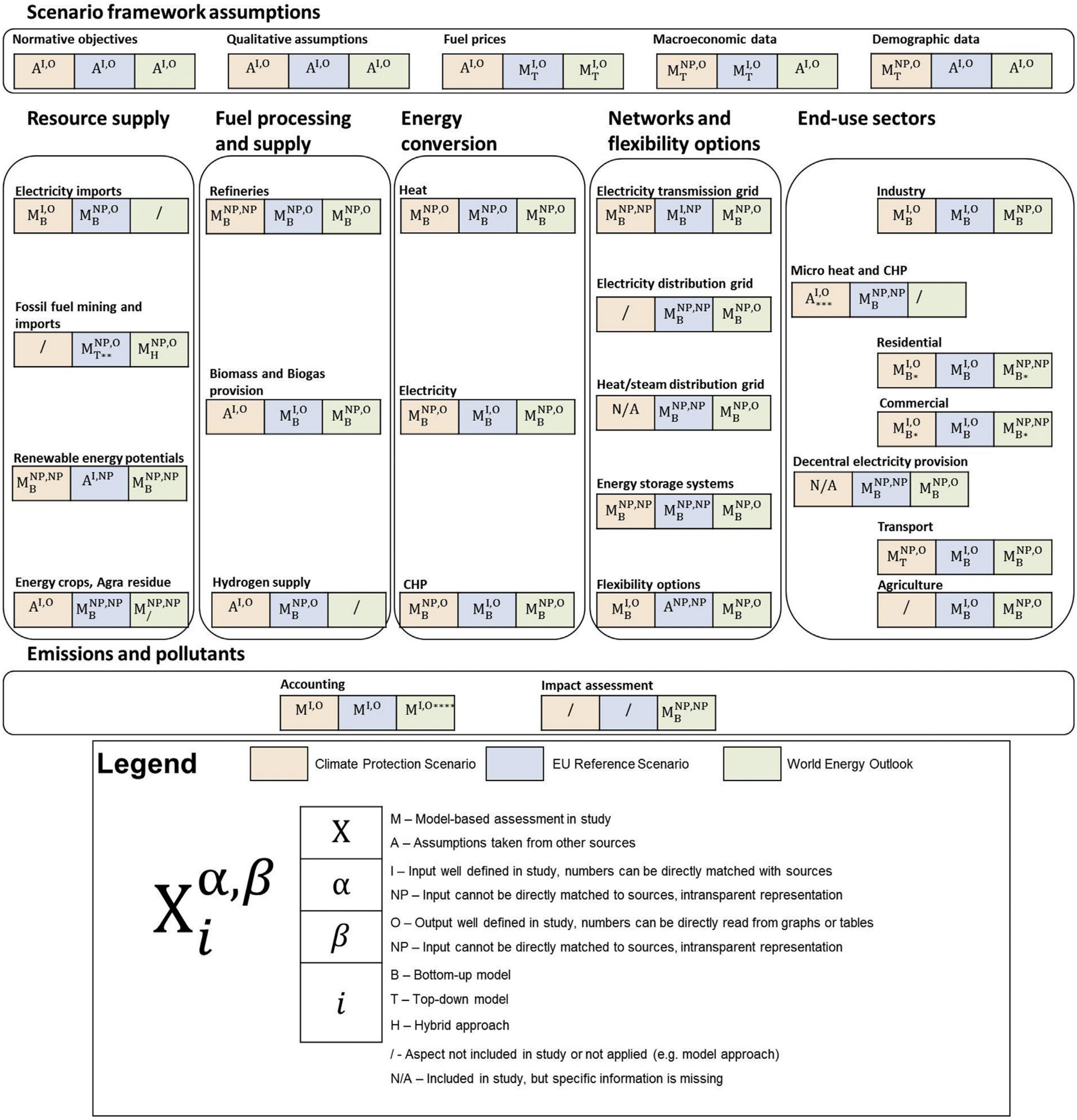


Fig. 3. Graphical representation of the traceability assessment for the three scenarios. Indication of the consideration of partial aspects: *Aggregated as building sector, **Gas sector only, ***Provided for heat pumps only, and ****CO_2 emissions only.

ERS. However, all three studies lack an in-depth analysis of the security of the supply under transformation scenario conditions (e.g. under extreme weather conditions).

3.3.3. Model coupling and model structures

All study reports provide graphical overviews of the involved models/modules, general interplay, and assignment to partial components of the energy system. However, note that such a representation never fully captures the interaction between the models for the reader. In all three studies, hybrid modelling approaches are applied for specific sectors or intersectoral analysis. Examples of 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 to derive the transport activity by transport mode and the 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 the electricity import to Germany (including capacity expansion planning) is derived from one specific model including the EUMENA region, while the capacity expansion and dispatch for Germany is calculated by two other specific models. It seems very difficult to achieve consistency with such a modelling approach and comprehensible explanations are missing. Furthermore, the model coupling of different sectors, especially power–heat, power–gas, and power–transport, must be considered to deal with fluctuating RES and multi-sector electrification, especially in deep defossilisation scenarios. However, the linkage of the models in terms of the 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 the models are often missing.

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

3.3.4. Data requirements and input–output data access

Requirements for the model parametrisation and definition of scenario input data strongly depend on the sectoral, technical, spatial, and temporal resolution of the studies. While the analysis of the CPS is only carried out at the national level, the ERS and WEO provide energy balances for 28 EU member states and 25 world regions and countries, respectively. However, the resolution of the demand sectors of the CPS is mostly higher, for example, regarding the building sector or the consideration of industrial processes. The study only occasionally 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, also states to have a considerable sectoral and technological resolution, but the data requirements and input data for submodels are mostly not provided. In the cases where data information is provided, the granularity is usually not sufficiently represented to be able to derive insights into the model. The ERS also uses models, which considerably differentiate the processes on the demand and supply sides. The study mentions the resolution of the data, but the detailed use must be identified using additional model documents (see Table 1).

The listing of data sources in the text or tables that are sometimes provided for certain numeric input data (in particular in the CPS and WEO) forces the reader to search any cited source using the corresponding number or, in case of doubt, to choose between numbers with the same information content. The ERS describes the input data using developed storylines and models. Some sources explaining the input data are available, but a more detailed database must be used for model-specific documents (e.g. for the PRIMES model). In the WEO, the input data are also not fully provided. Similar to the CPS, multiple sources are often listed for a certain parameter such 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 the readers. In all three studies, the main results are always provided in tables or figures, which contribute to the understanding of the reader. However, the data are not available in the maximum resolution of the modelling results according to the model descriptions.

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

3.3.5. Model validation

Model validation is generally based on the detailed discussion of the model strengths and weaknesses (e.g. parameters, variables, and formulation) and comparison of the model results with real-world data. The idea of validation is to verify if the model performance is as expected and if the models are in line with their objectives. Validation tests to check the model output can be performed internally (self-validation included in the study) and externally (feedback from other researchers). In addition, researchers can make the scenarios available to newspapers and other media (e.g. Twitter) and monitor the reactions to the articles and contributions. The reactions can then be considered in future scenarios. However, none of the three scenario studies state how the models are validated. Only limited output data were internally calibrated using similar studies. For example, the ERS validates the forest harvest removals by calibrating them using the most recent Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT) data from 2015. Furthermore, the economic and transport activity projections are validated by typical indicators such as the GDP or activity per capita. External validation is often reflected by the scientific and public perception, which is outside the scope of our analysis. Although the scenarios of the three studies are used as basis for other researchers in academia and the WEO is positively cited by public media, some criticism exists. For instance Ref. [28], reviewed the methodology of the IEA WEO studies and critically assessed the key assumptions and projections. The authors argued that the IEA may introduce a conservative bias by neglecting the dynamics and interlinkage in the energy and economy nexus. In general, the authors of the three studies should have provided 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. The public perception, as external validation, should be considered for future research.

3.3.6. Uncertainty treatment in the model and reporting

All three studies present and analyse scenario variants that show different possible developments. However, the uncertainties in the various assumptions and use of models to answer the research questions are not explicitly discussed. In addition, the presented pathways only represent a very narrow selection of possible future developments, for example, regarding the development of the economy, mobility, and society as a whole. On one hand, this is due to the defined narratives and implicit socioeconomic assumptions; on the other hand, this is based on the cost-optimizing approaches of the models in which the cost effects dominate and steer the developments. Assumptions of disruptive factors and elements and thus the possibility to check the robustness of the model results, conclusions, and derived policy recommendations are missing to a large extent. Regarding the different modelling approaches, there is a lack of documented sensitivity analyses showing the effects of variations on the model parametrisation. In general, the studies do not provide qualitative or quantitative uncertainties or explicit sensitivity analysis of individual scenarios but only contain general comments on the uncertainties mentioned in the model descriptions.

3.4. Further aspects

From a societal perspective, all studies neglect several relevant aspects and do not consider nor document significant implicit assumptions. In the case of the former, this concerns the definition of only one single path for the key economic and social drivers, as mentioned above. Significant other aspects include the lack of feedback loops from the change in the 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 the GDP and employment between the EMS and CS 80 scenarios.

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 participants. Assumptions or prerequisites regarding the development of political framework conditions are also insufficiently discussed and not integrated into the scenario context, for example, regarding the stronger national, European, or even global integration of the energy policy or possible effects of increasing isolation and confrontation on foreign policies. These aspects may lead to inconsistencies in the methodologies and input data. Regarding the development of technologies and their costs, the studies largely avoid speculative assumptions. As far as the considered technological innovations are documented and traceable, they represent today's achievable state of the art. However, rather speculative assumptions include, for example, assumptions about the future consumption by the population, renaissance of nuclear power, or possible impact of political measures.

The publication of the studies in the form of final reports also clearly differs with respect to, for example, the information available to the public via press releases and events and the suitability of the publications either to inform the interested public or as basis for further scientific scenario analyses. All studies lack parallel scientifically relevant publications in peer-reviewed journals and thus scientific discussions 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 media and in academia.

4. Recommendations and implications for scenarios developers

Based on our assessment of the three scenario studies, several recommendations can be made, which extend the more theoretical transparency checklist by Cao et al. [29].

4.1. Further improvements of the model transparency

4.1.1. Provide supplementary documents with well-documented input–output data

As discussed above, the input–output data are not completely and transparently documented. One reason might be that the core problem of energy data is that they are generally strictly protected. However, a more precise description of which data are used might improve the reproducibility and transparency of the models and resulting scenarios. An option could be the publication of simulated/artificial data with the main characteristics of the original data but ‘blurred’ critical information such as business-relevant information. The validation of this artificial data is however crucial and complex. For example, Wiese et al. [30] provided a unique open power system dataset for Europe, which can be used as a reference input to ESMs to improve the comparability of their results. Hirth et al. [31] also argued for an open data access and a recent tool allows the evaluation of the quality of input data [32].

4.1.2. Explain the model linkage and data exchange

Model coupling with either the same focus on one sector or different foci across the 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 insufficient because the data integration into the models is hardly comprehensible for outsiders. This is especially true for studies with model coupling, which transfer comprehensive data volumes between the different models (e.g. the ERS and 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 the models are soft- (i.e. manual data transfer between models) or hard-linked (i.e. direct data transfer between models) improves the understanding of the complexity and error-proneness of the coupling. However, the knowledge of the model coupling approach and data exchange is not enough. Lessons-learned publications for all coupling efforts with detailed descriptions of the used approaches, data exchange within these approaches, and difficulties would be helpful for future work [33].

4.1.3. Provide full open source and well-documented model codes

All three reviewed studies do not provide open source model codes. The demand for well-documented model codes was reported by Laugs and Moll in 2012 [34,35]. In the following years, several other contributions were made. For example, Morrison [36] viewed open source models as core aspects of publicly transparent and scientifically reproducible energy system modelling. The author focused on the legal aspects of existing open access models. Pfenninger et al. [37] provided a comprehensive overview of current open source ESMs focusing on open data. The authors indicated that the current trend is overwhelming, although the energy sector seems to lag behind other computer model societies. This optimistic perspective is supported by current grassroots developments such as openmod-initiative.org. The main advances of open source codes in addition to the reproducibility and transparency are the easy comparability of the scenarios and the higher efficiency in developing highly sophisticated and broadly approved ESMs [38,39]. The hope is that the provision of source codes and data might significantly speed up the developing processes. Another positive side effect is the broader acceptability in the scientific community.

4.2. Further improvements of the 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 the energy supply and demand are generally not explicitly addressed in scenario reports, for example, the cultural impacts on the acceptance of change processes or politics and state specifics with respect to the change processes and their effects on the interest groups. The combination of explicit, qualitative and quantitative context storylines and energy modelling in a consistent and transparent way could significantly help to improve the robustness of the scenario results and conclusions (see e.g. Ref. [40]). This may lead to the construction of comprehensive sociotechnical scenarios considering crucial aspects of the energy transition such as disruptive elements attributable to societal risks or opportunities [41]. Based on the construction of sociotechnical scenarios as ‘hybrid’ scenarios, the perspectives and methodologies can be combined in the future to create a truly interdisciplinary modelling approach [42].

4.2.2. Stakeholder integration

Stakeholders can be involved in the scenario development process or, subsequently, by commenting on the results (e.g. scientific publications, reports, or media articles). However, they were not included during the scenario creation in any of the reviewed studies. In the last decades, stakeholders were only partially included in the scenario design, for example, to discuss specific parameters of power plants with utilities or to publicly participate in local or regional government planning. Today, arguments about the inclusion of more stakeholders and even consumers become more important [43]. The inclusion of stakeholder opinions can be ‘measured’ in workshops [44], while the inclusion of consumers usually requires surveys [45]. Most of the energy scenarios and policies are derived from complex techno-economic analyses but rarely consider other types of relevant societal values and interests [46,47]. In this context, public perspectives can provide insights into potential societal opportunities and limitations of energy pathways and, in particular, answer the question regarding which aspects and configurations of the system change will provide a socially acceptable level of affordability, energy security, and environmental protection.

4.2.3. *Uncertainty analysis of the key input data*

The three reviewed policy-oriented scenario analyses did not provide uncertainty analyses of the key input data, which considerably reduces the robustness of the derived results. In principal, relevant uncertainties can be identified using sensitivity analysis, which is intended to derive the key driving forces. A stochastic approach is a way to include small (and well-understood) uncertainties of input data, for example, by Monte Carlo simulations, if the computing times allow multiple model runs. More unknown and significant uncertainties might be considered by different scenario variants. Recent studies showed that sensitivity analysis is widely used to analyse macroeconomic parameters (e.g. Ref. [48]) and energy technology costs, as prerequisites to determine investments (e.g. Ref. [49]), and technical parameters related to multiple research questions (e.g. Ref. [49]). The stochastic approach is mostly used for renewable energy system optimisation, for example, for multi-criteria system design [50], or to deal with the uncertainty in the availability of renewable resources [51].

4.2.4. *Common model structures and open data*

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

5. Conclusions

Although our study is limited to three case studies, we can compare the scenario results with overlapping geographical scopes and perform a systematic analysis of the narratives, assumptions, and applied methods and models. We provide a comprehensive approach to evaluate and compare the quality of scenario studies with a focus on the transparency within and beyond applied modelling approaches for a deep understanding of the scenario results. This analysis demonstrates that fulfilling the criteria of transparency, comprehensibility, and traceability requires a clear concept and certain documentation effort 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 report the essential aspects of the studies.

The results confirm that each model-based scenario study has strengths and weaknesses and significantly varies regarding the use of methods and models. Scenario studies often neglect aspects that can hardly be quantified, such as societal and environmental risks and opportunities, or only reflect a restricted spectrum of possible developments, for example, regarding the drivers of the energy demand. Furthermore, it is difficult or even impossible to evaluate the scenarios and their methodological background based on the final report only. All three studies refer to background material, that is, documentation of the models used, or to studies from which the results are used as assumptions for model parametrisation. Notable weaknesses of the studies include the weak transparency with respect to the model coupling and data access. The effort required to obtain a clear picture is unacceptable for people interested in these reports. Although the studies present graphs to visualise the applied models and their results, they often insufficiently describe the model interfaces, data exchange, harmonisation of assumptions, and iteration loops between the models. Furthermore, little information is provided on the model validation and a comprehensive uncertainty analysis of the key assumptions is missing. Thus, the necessity and suitability of the model usage regarding the research questions remain largely unclear to the reader. Therefore, more well-documented open source and open data studies are needed in the field of energy system analysis. Moreover, the authors of scenario study publications must pay more attention to reporting results comprehensible to the general public and to openly discussing the robustness and uncertainties of derived conclusions and policy implications.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.100380.

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