Development of a new modelling concept for providing initial consultation at a federal state level

Tim Mandel[1], Rainer Elsland

Fraunhofer-Institut für System- und Innovationsforschung ISI, Breslauer Str. 48, 76139 Karlsruhe, +49 721 6809-248, Tim.Mandel@isi.fraunhofer.de, www.isi.fraunhofer.de

Abstract:

In the context of variable power supply as well as structural changes in energy demand, decision-makers in German federal states are becoming an increasingly important target group for model-based consultation. However, given their typically high computational complexity and data needs, established modelling tools tend to be inappropriate for providing prompt quantitative assessments, so-called initial consultation. Against this background, the present study develops, applies and evaluates a new modelling tool, based on a complexity-reduced design. By performing a comparative assessment with an existing model-based scenario analysis for a selected federal state, the new modelling tool is shown to yield robust outputs. Methodical issues include the consideration of capital stock dynamics, as well as the definition of system boundaries. Nonetheless, the modelling tool provides useful insights for initial consultation at a federal state level.

Keywords: Energy system modeling, bottom-up analysis, renewable energies, energy efficiency

1 Motivation and research question

In the context of national commitments, international agreements and rapid technological progress, decision makers in Germany increasingly rely on wind power and photovoltaics (PV) to meet energy demand and to mitigate greenhouse gas (GHG) emissions. These technologies are frequently referred to as variable renewable energy sources (VRE) [1,2]. Given their intermittent nature, VRE are expected to have distinct techno-economic impacts on power system operation, including the need for flexible power generation [1,3–5]. In addition, driven by structural changes in energy demand, power system operation is challenged by an increasing electrification in the transport and heating sectors, often referred to as the coupling of demand sectors [5–7]. Against this background, the power supply system is subject to an ongoing transition process with a multitude of competing flexibility options. These include thermal power plants, storage facilities, power-to-heat (P2H) and power-to-gas (P2G) converters, as well as demand side management (DSM) [1,4,8].

In Germany, decision-makers in federal states (Bundesländer) are considered increasingly important for managing this transition process, with policy competences ranging from renewable energy capacity expansion to GHG target setting [9,10]. Given the diverse uncertainties associated with this transition process, decision-makers in German federal

[1] Jungautor

states frequently rely upon model-based scenarios to design policies and to assess cost-effective investment pathways [11,12]. In this context, the concept of initial consultation is gaining importance. It can be understood as a starting step in performing scenario analyses, with the overall purpose of gauging the major influencing factors for certain outcomes – such as technology costs and fuel prices – and to enable decision-makers to comprehend the consequences of their actions in a quick and stylized manner before performing more elaborate modelling studies. In this way, initial consultation can allow for a better understanding of technology alternatives and related political decisions [13–16]. However, providing initial consultation to federal state decision-makers is currently subject to two major challenges.

On the one hand, some modelling approaches applied in federal state scenario analyses tend to be overly simplistic with regard to the techno-economic challenges associated with VRE operation. For example, in a scenario study for Lower Saxony, Kralemann et al. [17] assume a number of yearly full load hours for VRE generators while short-term mismatches between electricity supply and demand seem to be disregarded. As argued by multiple authors, such simplified approaches can result in mistaken signals regarding system costs, greenhouse gas abatement potentials and the ability of power systems to accommodate VRE [2,4,5]. On the other hand, some modelling approaches appear to be too complex for providing initial consultation. For example, Schmidt et al. [18] perform an elaborate scenario analysis for the case of Baden-Württemberg, using an ensemble of detailed energy system models. This approach has two major shortcomings – comprehensive data needs and computation times [19–21]. Data needs arise from a high degree of technical detail, resulting in a lengthy parametrization and calibration process of up to several weeks [14,22]. With respect to computation time, models taking detailed account of the temporal, technical and spatial aspects of VRE operation typically run linear or mixed-integer optimization methods that are numerically complex and thus time-intensive [2,5,23].

For these reasons, we argue that a model particularly designed for providing initial consultation at a federal state level should be characterized by low data needs and short computation times, whilst accounting for the techno-economic impacts of VRE deployment in power systems and structural changes in energy demand. Recent research has introduced novel methodologies to capture these dynamics without becoming unwieldy in terms of data needs and computation times, including reduced-form optimization algorithms, parametrizations, and time series aggregations [1–3].

Drawing upon recent approaches, the present research attempts to develop a novel modelling tool particularly suitable for providing initial consultation at a German federal state level. Accordingly, it addresses the question to what extent a modelling tool with reduced levels of data needs and computational complexity can yield robust results in scenario analyses for investigating the long-term dynamics between VRE supply and structural changes on the demand-side of the energy system at a German federal state level. The remainder of this paper is organized as follows: Section 2 introduces the features of the newly developed modelling tool FederalPlan. In Section 3, the tool is evaluated in a comparative assessment for the federal state of Baden-Württemberg. Section 4 provides a critical discussion of the plausibility of the tool's outcomes. Finally, Section 5 concludes this paper.

2 Methodology: Development of a modelling tool for initial consultation

As described previously, power system transformation, along with the need for flexibility options, does not solely depend on the deployment of variable renewable energies, but likewise on the anticipated evolution of energy demand and its structural changes. Approaching scenario studies from the power supply side only thus risks excluding essential dynamics within the entire energy system, which may lead to misinterpretations and selective policy interventions [11,24,25]. Against this background, the newly developed modelling tool FederalPlan provides an integrated perspective of the energy system (Figure 1).

One of its essential features is the projection of future energy and power demand in the different demand sectors, including options for fuel and technology substitution towards electrification, improvements in energy efficiency, and socio-economic impacts. For this purpose, a bottom-up accounting framework is set up, covering four demand sectors (residential, transportation, industry, tertiary), up to eight end-use categories per sector (space heating, hot water, lighting etc.), and a multitude of technologies per end-use. Given the accounting logic of the demand module [26,27], demand technology choices and market behavior in the target year are subject to exogenous parameters set by the modeler. Creating demand scenarios for a single federal state essentially requires a historic energy balance as well as general statistics for the base year, such as population and GDP. Recent energy balances are available from [28], while federal state's statistical offices provide the necessary socio-economic statistics.

The resulting demand projections are used as input for two sub-features of the model. On the one hand, the model provides endogenous modelling of future electrical load curves. This takes into account that the shape of the load curve is likely to change in response to structural changes, which, in turn, may have system-wide implications, such as a greater need for managing load peaks and troughs through flexibility options [29]. For this purpose, a partial decomposition approach is applied [30]. It disaggregates the base year load curve by means of application-specific load profiles and reassembles the target year curve according to the application-specific electricity demand projections. Overall, the FederalPlan model comprises a total of 23 application-specific load curves, explaining about 40% of total system load in the application example set out in Section 3. On the other hand, the model performs an endogenous assessment of potentials for demand side management (DSM). The focus is on the practical potential, i.e. all facilities and devises technically suitable for DSM that can be controlled by existing ICT infrastructure and that are subject to acceptance on the part of consumers [31]. The potential assessment follows a bottom-up approach introduced by Styczynski et al. [32]. It characterizes processes and appliances with regard to their potential load increase (negative balancing power), load reduction (positive balancing power) and the typical shifting times. The potentials determined are used in the supply module of the model to represent DSM as a flexibility option.

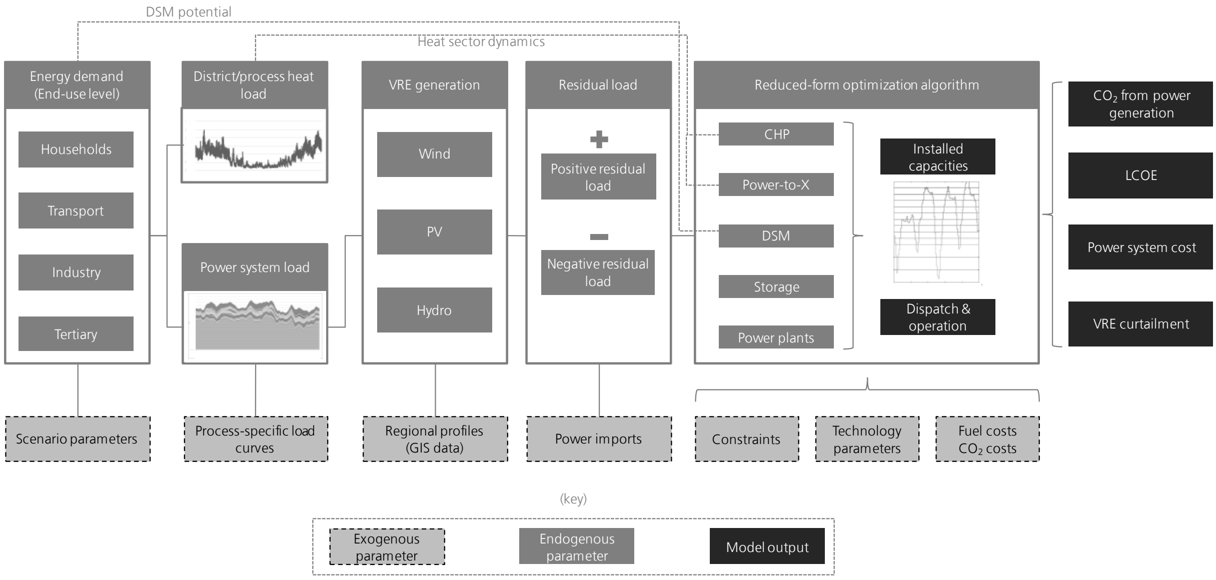

Fig. 1: Overview of the structure and procedure of the FederalPlan model. Source: author's own.

The power supply module of the FederalPlan tool comprises two essential components, based on a recent approach introduced by Lunz et al. [16]. In a first step, the power generated from wind, solar and hydropower is modelled for the target year and subtracted from the system load to obtain the hourly residual load. For this purpose, hourly system load curves for most federal states can be obtained from the respective transmission system operators, for instance for the state of Baden-Württemberg [33]. Likewise, location-specific hourly generation profiles for VRE at a federal state level are available from public data [34].

Subsequently, the model performs a reduced-form cost-based optimization of power supply configurations in the target year, based on the algorithm introduced in [16]. More specifically, it simultaneously optimizes both investments into power plants and flexibility options, as well as their dispatch with hourly resolution over the full 8760 hours of a year in order to minimize total system costs. These costs, expressed by the levelized cost of electricity (LCOE), represent the sum of annuities of installed capacities, fuel and CO_2 emission costs, fixed operation and maintenance costs, as well as variable ramping costs for power plant start-ups. The latter parameter accounts for warm and cold starts after idle operation, providing a simplified image of technical detail in power plant operation.

Model constraints include the balance of power supply and demand at every hourly time step, as well as exogenous settings, such as limits for installed capacities of certain technologies. Decisions are made from the perspective of a central planner with perfect information, with costs following a socioeconomic least-cost strategy without consideration of business-economic market strategies [35,36]. Following [16], the technology portfolio comprises a large variety of flexibility options, including conventional power plants, CHP, energy storage, power-to-X, and DSM (Table 1). Considering system boundaries, the single federal state under consideration is set as the only internal region [37], requiring the balancing of power generation and system load within federal state boundaries. Representing other federal states as well as neighboring countries, a non-specified external region provides an exogenously amount of power imports to the federal state. Power exports are not explicitly modelled.

Table 1: Power supply and flexibility options in the FederalPlan model, including possible fuel configurations. Source: author's own.

Thermal power plants				
Steam turbine (hard coal, lignite, lignite /w CCS)	Combined-cycle gas turbine (natural gas, biomethane)	Open-cycle gas turbine (natural gas, biomethane)	Engine power station (natural gas, biomethane)	Wood power station (biomass)
Combined heat and power (CHP)				
Steam turbine (hard coal)	Open-cycle gas turbine (natural gas)	Combined-cycle gas turbine (natural gas)	Industrial engine power plant (natural gas)	-
Energy storage				
Pumped hydro-electric storage	Adiabatic compressed air storage	Hydrogen storage	Methane storage	Battery storage
Demand side management (DSM)				
DSM households	DSM industry	DSM trade, commerce, services	-	-
Power-to-X				
Power-to-heat electrode boiler	Power-to-gas methanization	-	-	-

Overall, one model run results in a power supply configuration with minimized costs at given parameters and constraints for a single target year. Using the reduced-form optimization algorithm, results are provided instantaneously for conventional power plants, CHP and power-to-X technologies. A more elaborate model run, including storage and DSM as additional flexibility options, takes about 4 hours on a standard PC. The entire model, including both energy demand and supply, is implemented in Microsoft Excel and Visual Basic for Applications (VBA), allowing for a quick user-friendly setup of scenarios. In the following, a comparative application of the FederalPlan model is presented.

3 Results: Application of the modelling tool in a comparative case study

Considering the simplified design of the FederalPlan model, a key concern is its ability to deliver robust outputs in long-term scenario analyses. Against this background, we compared selected power supply-related outputs of the FederalPlan model to an established scenario report for the federal state of Baden-Württemberg in the target year 2050 [18]. The power sector projections in this report are based on an unnamed model hereinafter referred to as BW-POWER. Table 1 provides a qualitative comparison of the main features of FederalPlan and BW-POWER. An essential difference lies in the modelling logic for power supply. While FederalPlan performs a cost-based optimization of generation capacities and dispatch for a single target year, BW-POWER model applies an accounting framework, tracking generator lifetimes and adding new capacities based on narrative exogenous assumptions. In turn, both models correspond in the definition of system boundaries, regarding the federal state as the only internal region, subject to exogenous imports and without consideration of power exports to other federal states and countries.

In order to enable comparability in the comparative assessment, input parameters and boundary conditions in FederalPlan are aligned to those of BW-POWER. This includes fuel and CO_2 prices, VRE capacities and generation, the amount of power imports and others. Technology prices for different flexibility options were not provided in the reference report. Here, the FederalPlan model draws upon recent numbers for Germany provided in [16], which are based on technology learning curves. Based on the scenario report [18], the comparative assessment is performed for two scenarios, with the business-as-usual scenario (BAU2050) being in the focus of the present analysis.

Table 1: Qualitative comparison of power supply-related features in the models FederalPlan and BW-POWER. Source: author's own.

	FederalPlan	BW-POWER
General features		
Modelling logic	Optimization	Accounting
Temporal detail		
Temporal resolution	Hourly	Yearly
Time steps	single target year (“greenfield”)	10 years
Technical detail		
Technological portfolio	Power plants; CHP; Storage; P2X; DSM	Power plants; CHP; Storage; P2X
Technical detail (power plants)	Startup/ramping costs	-
Spatial detail		
System boundaries	Single internal region, exogenous imports	Single internal region, exogenous imports
Spatial resolution (VRE)	Regional VRE generation profiles	Regional VRE generation profiles

Before analyzing the results of the comparative assessment, a number of selected demand-related outputs of the FederalPlan model are presented in order to highlight its features in this respect. Figure 2 shows demand projections for the example of the residential sector in the BAU2050 scenario, divided by fuel and by end-use. Following the reference report [18], final energy demand decreases from 265 to 232 PJ between 2015 and 2050, with space heating demand accounting for the largest share. In turn, electricity consumption increases by 25% between 2015 and 2050, mostly due to the diffusion of heat pumps as well as higher equipment rates for white appliances. Note that in the FederalPlan model, demand projections are based on an accounting framework, i.e. exogenous technology shares and other scenario parameters are set by the modeler.

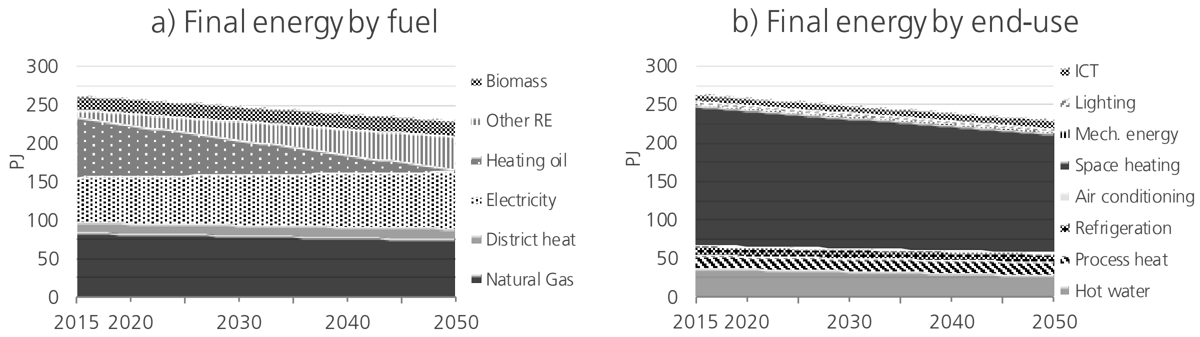

Fig. 2: Demand projections for the residential sector in the BAU2050 scenario, as computed by the FederalPlan model. a) Final energy consumption by fuel. b) Final energy consumption by end-use. Years between 2015 and 2050 are interpolated for illustrative purposes. Source: author's own.

Based on the technology-discrete demand projections and the aforementioned partial decomposition approach, the FederalPlan model computes alterations in the hourly system load curve for the target year. As given in Figure 3, the diffusion of heat pumps, electric vehicles and other technologies in the BAU2050 scenario leads to distinct load curve alterations. Overall, not illustrated in this chart, peak load increases from 13.00 GW in 2015 to 15.03 GW in 2050, giving rise to additional generation capacity necessary.

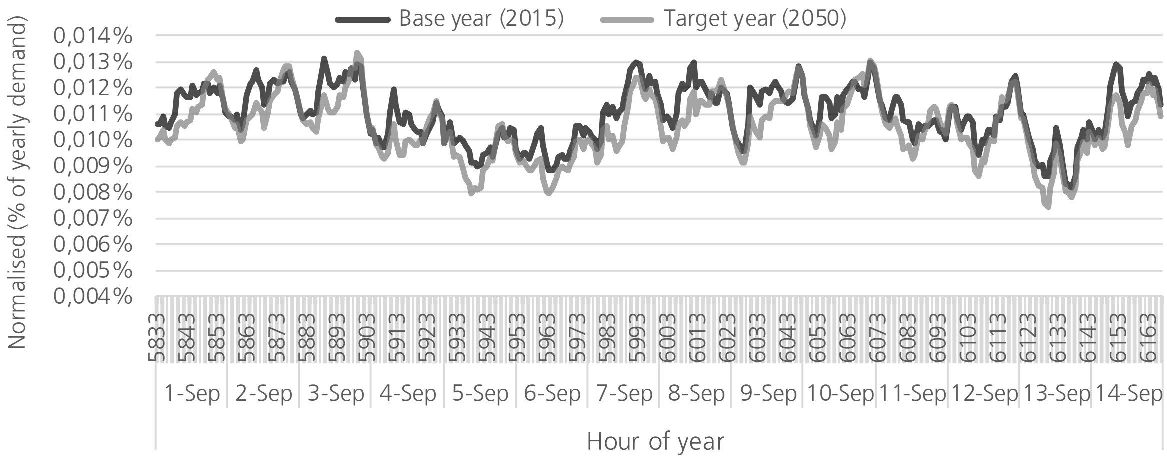

Fig. 3: Load curve projection for the BAU2050 scenario, as computed by the FederalPlan model. Profiles are normalized to annual demand, representing two weeks in September. Source: author's own.

After having considered the demand side of the energy system, supply-related outputs of FederalPlan are compared to the ones obtained from the BW-POWER model. First, the two models are compared with regard to the amount of reserve power projected, i.e. all generation capacity excluding the contribution of VRE that is necessary to cover positive residual load at all times. Considering Figure 4a), it appears that the BW-POWER model underestimates the reserve capacity needed in the BAU2050 scenario. This can be attributed to the yearly resolution applied in BW-POWER, which contrasts with the hourly resolution in the FederalPlan model and its consideration of possible load curve alterations. Accordingly, FederalPlan may take more explicit account of temporal mismatches between VRE generation and power demand. Regarding the technology mix, there are obvious differences in the capacities for hard coal and biomethane. These can be attributed to the narrative accounting approach in BW-POWER, taking into account long-lived capital assets installed in previous years. This contrasts with the greenfield approach applied in FederalPlan, performing a cost-based optimization of generation capacity in the target year 2050. Likewise, considering storage deployment, BW-POWER takes account of the existing pumped hydro plants in Baden-Württemberg, assuming their continuous operation until 2050. In contrast, FederalPlan projects the deployment of methane storage facilities for long-term storage of VRE surpluses, as well as DSM for load shifting.

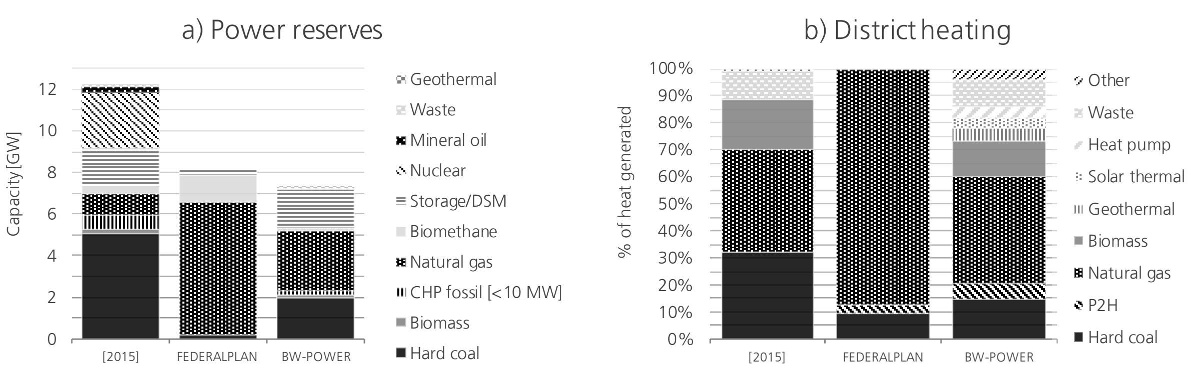

Fig. 4: Comparison of outputs computed by FederalPlan and BW-POWER in the BAU2050 scenario. a) Power reserves (excl. VRE). b) District heating supply. Source: author's own.

Second, the deployment of combined heat and power plants (CHP) and power-to-heat electrode boilers (P2H) in district heating networks is analyzed. Figure 4b) displays the technology shares in district heating supply in the BAU2050 scenario, as computed by FederalPlan and BW-POWER. The findings indicate that FederalPlan estimates the contribution of hard coal-fired CHP and P2H electrode boilers reasonably well. However, the share of natural gas in total heat generated is clearly overestimated in comparison to BW-BAU2050. This can be attributed to the fact that the district heating-related technology portfolio in the FederalPlan model is limited, taking no account of biomass- and waste-fired CHP, geothermal and solar thermal energy, as well as heat pumps. However, given its accessible setup in Excel, these technologies can be implemented in future versions of the model to provide a more diverse image of district heating supply configurations.

Third, CO_2 emissions from power supply in the target year 2050 are compared between FederalPlan and BW-POWER. Figure 5 displays the corresponding annual emissions for the baseline, as well as the respective model projections. FederalPlan suggests annual emissions of 4.66 mill. tCO_2 for the target year 2050, corresponding to a 73.4% reduction relative to 1990 levels. In contrast, BW-POWER presumes 9.00 mill. tCO_2 in 2050, reflecting only a 48.7% reduction compared to 1990. This difference can be attributed to the power supply-related modelling logic in the two models, contrasting an optimization approach for a single target year (FederalPlan) with an accounting approach, covering transitions over several decades (BW-POWER). More specifically, FederalPlan does not consider existing capital assets in the power sector, deploying low-carbon capacities in response to technology, fuel and CO_2 prices in the target year 2050. In turn, BW-POWER takes no account of prices in determining future capacities, with deployment being based on narrative assumptions of the modelers, such as the continuous operation of incumbent hard-coal capacities until 2050. Accordingly, it can be argued that BW-POWER does not provide a reliable reference for a comparative assessment. Instead, the supply-related outputs in FederalPlan should be compared against a detailed capacity expansion and dispatch model [1], taking detailed account of both capital stock and price dynamics.

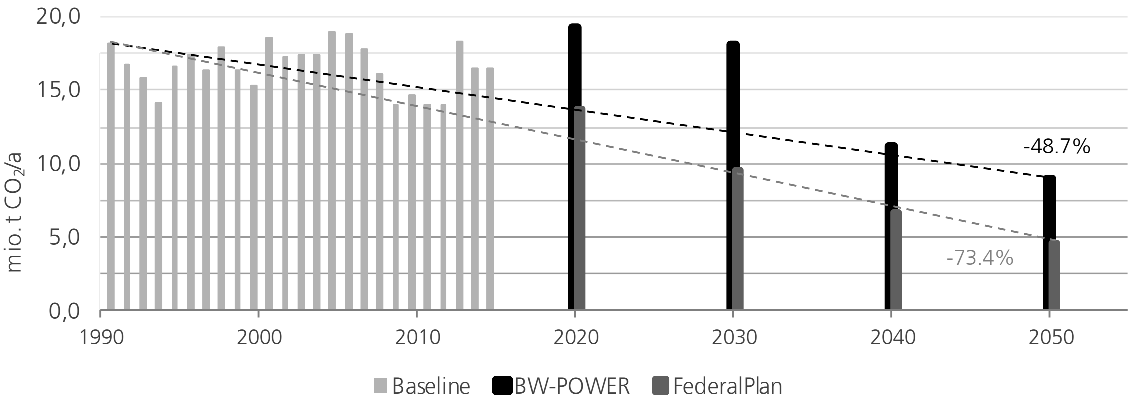

Fig. 5: Development of CO_2 emissions from power generation in the BAU2050 scenario and reduction relative to the base year 1990, as projected by FederalPlan and BW-POWER. Values for the timespan 2020-2040 are interpolated logarithmically for the FederalPlan cases. Source: author's own.

In addition to the comparative assessment, sensitivity analyses are performed for the FederalPlan model. Parameters investigated include the CO_2 price, the discount rate, the shape of the load curve, as well as the consideration of power plant startup costs. In short, variations in the former two parameters yield reasonable model outputs. Moreover, the shape the hourly shape of the endogenously modelled load curve is found to have an influence on the deployment and dispatch of power plants and flexibility options, influencing the alignment of VRE supply and power demand, as well as the utilization of baseload generators. This effect should be scrutinized in future research in order to provide additional insights. Concluding this section, the FederalPlan model appears to provide robust results in scenario analyses at a federal state level. Differences in the comparative assessment can mostly be attributed to the contrasting modelling logic between the two models under consideration. Based on these results, the following section provides a critical reflection on the modelling approach selected in FederalPlan, highlighting possible improvements.

4 Discussion

In order to be useful for providing initial consultation, the FederalPlan is designed in a way to minimize data needs and computational complexity. The corresponding simplifications are associated with issues in terms of temporal, technical and spatial detail that are discussed in the following.

Considering temporal detail, a major asset of the FederalPlan is its hourly resolution, providing non-aggregated time series of power supply and system load and allowing for detailed analyses of load shifting performed by storage and DSM facilities. However, regarding scenario time steps, FederalPlan examines a single target year and does not explicitly model capital stock turnover as well as existing and written-off assets in the power sector. These dynamics are only implicitly taken into account by applying technology costs that are based on learning curves and corresponding assumptions on technology production volumes [7,16]. As shown in the results, this greenfield approach may potentially underestimate the effect of incumbent fossil power generators on the electricity mix and corresponding CO_2 emissions in the target year. To capture these dynamics, an enhanced version of the FederalPlan model could include a simple non-exponential vintaging approach, tracking the construction year for all existing capacities and decommissioning them after their technical lifetime, with the optimization algorithm selecting new capacities according to their LCOE [5]. Overall, this could enable a more realistic representation of capital stock dynamics. In spite of this possible improvement, the greenfield approach can be useful for providing guidance in the present. It provides insights on how the power system should be designed today in order to attain desired targets in 2050, preventing stranded assets and lock-in effects. For technologies that are likely to be significant in 2050, a corresponding support of research and development and other policy initiatives at present can help attain the techno-economic progresses needed in future [16].

With regard to technical detail, the two major issues in the FederalPlan model include the technological portfolio and the consideration of operational constraints of power plants and flexibility options. Considering the former, FederalPlan features a multitude of conventional power plants and flexibility options. However, particularly in scenarios with ambitious GHG reduction targets, additional renewable energy-based generators are necessary to represent the full range of possibly cost-effective technology options. As for operational aspects, FederalPlan features a cost parametrization of operational constraints for power plants. This parametrization does not consider the actual technical feasibility of the dispatch projected by the model, with generator dispatch in reality being constrained by minimum load levels, partial load efficiencies and ramping capabilities [1,38]. Based on existing research, this simplification may imply an underestimation of operational costs in the generation mix and of corresponding CO_2 emissions [39,40].

Regarding spatial detail, FederalPlan has issues in the definition of system boundaries. The approach of defining the federal state as the only internal region enables a low degree of computational complexity as well as a quick setup of scenarios. However, it does not take account of the market-based power exchange that federal states are integrated into in reality. Furthermore, it neglects the potential benefits of spatial shifting as a flexibility option for VRE surpluses [1]. Consequently, the FederalPlan model might overstate the long-term investment needs for transforming the generation part of the power system. In conclusion, applications of the FederalPlan model should take explicit account of these limitations in performing scenario analyses at a federal state level.

5 Conclusion

The present study is based on the assertion that the appropriateness of a modelling tool for providing initial consultation can be enhanced by making reasoned simplifications in terms of model detail, in order to achieve a low degree of data needs and computational complexity. Accordingly, the question was raised to what extent a modelling tool with reduced levels of detail can yield robust results in scenario analyses for investigating the long-term dynamics between VRE supply and energy demand at a federal state level.

Against this background, the present study introduced the development of the novel modelling tool FederalPlan, which is characterized by reduced levels of temporal, technical and spatial detail. One of its key elements is a reduced-form optimization algorithm, resulting in considerably lower computation times compared to established linear- and mixed-integer programming approaches. Moreover, the model is characterized by limited data needs. While the supply side only requires a system load curve for the given region as well as the anticipated VRE capacities, the demand-side can be based on energy balances readily available for single federal states or for Germany. Overall, while the field of energy systems modeling clearly offers more sophisticated approaches, the FederalPlan model allows for analyzing a large set of parameter variations in a reasonable amount of time [7,16]. This is a major asset for providing initial consultation, enabling decision makers to comprehend how changes in parameters and boundary conditions affect scenario outcomes.

Considering the robustness of its outputs, the systematic comparative assessment set up for this study has revealed that, under similar boundary conditions, the outputs computed by the FederalPlan model show some similarities with the ones from the reference model. In turn, there are differences with regard to the generation mix, as well as long-term CO_2 emissions from power supply. These differences can mostly be attributed to the different modelling logics applied in the two models, contrasting cost optimization with a narrative accounting approach. Sensitivity analyses performed for the FederalPlan model yield plausible outcomes. In conclusion, the results obtained from the FederalPlan model can be generally considered robust, while a more appropriate comparison with a more detailed capacity expansion and dispatch model should be carried out to provide additional insights.

6 References

[1] IRENA. Planning for the Renewable Future: Long-term modelling and tools to expand variable renewable power in emerging economies. Abu Dhabi: International Renewable Energy Agency; 2017.

[2] Collins S, Deane JP, Poncelet K, Panos E, Pietzcker RC, Delarue E et al. Integrating short term variations of the power system into integrated energy system models: A methodological review. Renewable and Sustainable Energy Reviews 2017;76:839–56.

[3] Johnson N, Strubegger M, McPherson M, Parkinson SC, Krey V, Sullivan P. A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system. Energy Economics 2017;64:651–64.

[4] Foley AM, Ó Gallachóir BP, Hur J, Baldick R, McKeogh EJ. A strategic review of electricity systems models. Energy 2010;35(12):4522–30.

[5] Pietzcker RC, Ueckerdt F, Carrara S, Boer HS de, Després J, Fujimori S et al. System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. Energy Economics 2017;64:583–99.

[6] Stephanos C, Höhne M-C (eds.). Coupling the different energy sectors: Options for the next phase of the energy transition. München: acatech – Deutsche Akademie der Technikwissenschaften e. V; 2018.

[7] Byfield S, Vetter D. Flexibility concepts for the German power supply in 2050: Ensuring stability in the age of renewable energies. München: acatech – Deutsche Akademie der Technikwissenschaften; 2016.

[8] Elsner P, Fischedick M, Sauer DU. Flexibilitätskonzepte für die Stromversorgung 2050: Technologien – Szenarien – Systemzusammenhänge. München: acatech – Deutsche Akademie der Technikwissenschaften; 2015.

[9] Diekmann J, Groba F. Erneuerbare Energien: Brandenburg und Bayern führen im Ländervergleich. DIW Wochenbericht 2012;79(50):3–11.

[10] Wurster S, Köhler C. Die Energiepolitik der Bundesländer: Scheitert die Energiewende am deutschen Föderalismus? In: Hildebrandt A, Wolf F, editors. Die Politik der Bundesländer. Wiesbaden: Springer; 2016, p. 283–314.

[11] Behn R, Byfield S (eds.). Consulting with energy scenarios: Requirements for scientific policy advice. Munich: National Academy of Science and Engineering; 2016.

[12] Cao K-K, Cebulla F, Gómez Vilchez JJ, Mousavi B, Prehofer S. Raising awareness in model-based energy scenario studies—a transparency checklist. Energy, Sustainability and Society 2016;6(1):1–20.

[13] IRGC. Assessment of Future Energy Demand: A Methodological Review Providing Guidance to Developers and Users of Energy Models and Scenarios. Lausanne: International Risk Governance Council (IRGC); 2015.

[14] Mai T, Logan J, Blair N, Sullivan P, Bazilian M. RE-ASSUME: A Decision Maker's Guide to Evaluating Energy Scenarios, Modeling, and Assumptions. Paris: International Energy Agency; 2013.

[15] Strachan N, Fais B, Daly H. Reinventing the energy modelling–policy interface. Nature Energy 2016;1(3):16012.

[16] Lunz B, Stöcker P, Eckstein S, Nebel A, Samadi S, Erlach B et al. Scenario-based comparative assessment of potential future electricity systems – A new methodological approach using Germany in 2050 as an example. Applied Energy 2016;171:555–80.

[17] Kralemann M, Schröder S, Mannstedt T. BUND-Szenario: Energieversorgung in Niedersachsen im Jahr 2050. Hannover: Bund für Umwelt und Naturschutz Deutschland; 2018.
[18] Schmidt M, Fuchs A-L, Kelm T, Abdalla N, Bergk F, Fehrenbach H et al. Energie- und Klimaschutzziele 2030. Stuttgart (i.a.): ZSW/ifeu/Öko-Institut/Fraunhofer ISI/Hamburg Institut; 2017.
[19] Crespo del Granado P, van Nieuwkoop RH, Kardakos EG, Schaffner C. Modelling the energy transition: A nexus of energy system and economic models. Energy Strategy Reviews 2018;20:229–35.
[20] Després J, Hadjsaid N, Criqui P, Noirot I. Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. Energy 2015;80:486–95.
[21] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews 2014;33:74–86.
[22] Greening LA, Bataille C. Bottom-up models of energy: across the spectrum. In: Evans J, Hunt LC, editors. International Handbook on the Economics of Energy. Cheltenham: Edward Elgar; 2009, p. 257–284.
[23] Pfenninger S. Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. Applied Energy 2017;197:1–13.
[24] Pfenninger S, Hirth L, Schlecht I, Schmid E, Wiese F, Brown T et al. Opening the black box of energy modelling: Strategies and lessons learned. Energy Strategy Reviews 2018;19:63–71.
[25] van Beeck NMJP. Classification of Energy Models. Tilburg: Tilburg University; 1999.
[26] Herbst A, Toro F, Reitze F, Jochem E. Introduction to Energy Systems Modelling. Swiss Journal of Economics and Statistics 2012;148(2):111–35.
[27] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Applied Energy 2016;169:607–28.
[28] Länderarbeitskreis Energiebilanzen. Energie- und CO2-Bilanzen. [June 18, 2018]; Available from: http://www.lak-energiebilanzen.de/.
[29] Boßmann T, Staffell I. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy 2015;90:1317–33.
[30] Boßmann T, Elsland, Lickert, Fridolin, Wietschel M. The German load curve in 2050: structural changes through energy efficiency measures and their impacts on the electricity supply side. In: ECEEE, editor. ECEEE 2013 Summer Study; 2013, p. 1199–1211.
[31] Gils HC. Assessment of the theoretical demand response potential in Europe. Energy 2014;67:1–18.
[32] Styczynski Z, Sauer DU (eds.). Demand-Side-Management im Strommarkt: Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“. München: acatech (Deutsche Akademie der Technikwissenschaften); 2015.
[33] Transnet BW. Kennzahlen: Lastverlauf (Netzeinspeisung). [October 01, 2018]; Available from: https://www.transnetbw.de/de/transparenz/marktdaten/kennzahlen.
[34] Pfenninger S, Staffell I. Renewables.ninja: Hourly simulations of wind and solar output. [September 23, 2018]; Available from: https://www.renewables.ninja/.

[35] Lund HH. Renewable energy systems: A smart energy systems approach to the choice and modeling of 100% renewable solutions. Boston: Academic Press; 2014.
[36] Scholz Y. Renewable energy based electricity supply at low costs: Development of the REMix model and application for Europe. Stuttgart: Universität Stuttgart, Institut für Thermodynamik und Wärmetechnik; 2012.
[37] Dodds PE, Keppo I, Strachan N. Characterising the Evolution of Energy System Models Using Model Archaeology. Environmental Modeling & Assessment 2015;20(2):83–102.
[38] International Energy Agency (IEA). The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems. Paris: International Energy Agency; 2014.
[39] Welsch M, Deane P, Howells M, Ó Gallachóir B, Rogan F, Bazilian M et al. Incorporating flexibility requirements into long-term energy system models – A case study on high levels of renewable electricity penetration in Ireland. Applied Energy 2014;135:600–15.
[40] Poncelet K, Delarue E, Six D, Duerinck J, D'haeseleer W. Impact of the level of temporal and operational detail in energy-system planning models. Applied Energy 2016;162:631–43.