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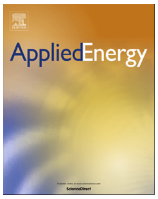

Scenario-based comparative assessment of potential future electricity systems – A new methodological approach using Germany in 2050 as an example

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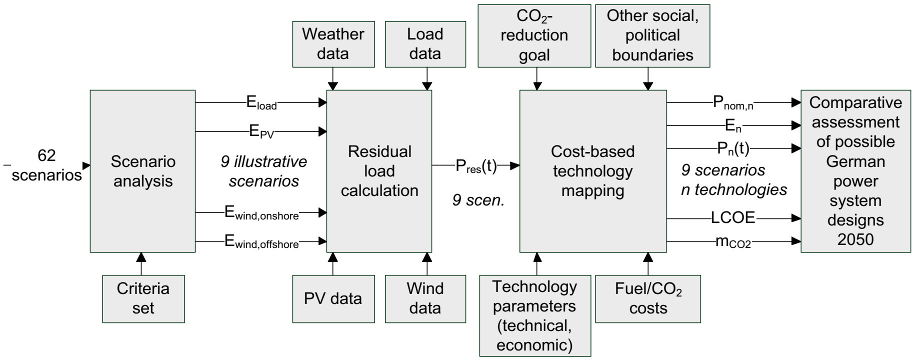
HIGHLIGHTS

- Method for evaluation and comparison of potential future electricity systems.
- Newly developed algorithm defines the mix of technologies providing flexibility.
- Algorithm has a very short runtime allowing for comprehensive parameter variations.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper a new method for the evaluation and comparison of potential future electricity systems is presented. The German electricity system in the year 2050 is used as an example. Based on a comprehensive scenario analysis defining a corridor for possible shares of fluctuating renewable energy sources (FRES) residual loads are calculated in a unified manner. The share of electricity from PV and wind power plants in Germany in the year 2050 is in a range of 42–122% and the load demand has a bandwidth of around 460–750 TWh. The residual loads are input for an algorithm that defines a supplementary mix of technologies providing flexibility to the system. The overall system layout guarantees the balance of generation and demand at all times. Due to the fact that the same method for residual load calculation and mixture of technologies is applied for all scenarios, a good comparability is guaranteed and we are able to identify key characteristics for future developments. The unique feature of the new algorithms presented here is the very fast calculation for a year-long simulation with hourly or shorter time steps taking into account the state of charge or availability of all storage and flexibility technologies. This allows an analysis of many different scenarios on a macro-economic level, variation of input parameters can easily be done, and extensive

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sensitivity analysis is possible. Furthermore different shares of FRES, CO_2-emission targets, interest rates or social acceptance of certain technologies can be included. The capabilities of the method are demonstrated by an analysis of potential German power system layouts with a base scenario of 90% CO_2-reduction target compared to 1990 and by the identification of different options for a power sector with a high degree of decarbonisation. The approach also aims at a very high level of transparency both regarding the algorithms and regarding the input parameters of the different technologies taken into account. Therefore this paper also gives a comprehensive and complete overview on the technology parameters used. The forecast on all technologies for the year 2050 regarding technical and economic parameters was made in a comprehensive consultation process with more than 100 experts representing academia and industry working on all different technologies. An extensive analysis of options for the design of potential German energy supply systems in 2050 based on the presented methodology will be published in a follow-up paper.

1. Introduction

The paper presents a newly developed method for the evaluation and comparison of potential future electricity systems. It was developed within the Academies' project "Energy Systems of the Future". Within this project the working group "Flexibility Concepts" aimed at comparing the flexibility demand and different ways to provide the required flexibility for potential future German electricity systems in the year 2050. Flexibility in this case is defined as all measures to balance fluctuating generation from PV and wind power and the load demand. That can be flexible generation (conventional power plants, concentrated solar power, geothermal energy), storage technologies (e.g. batteries, hydrogen storage), demand-side-management (DSM) and power-to-X-technologies. The approach is described using the German power system as an example. However, the method can be applied to any other power supply system as long as sufficient transmission grid capacity is available for the region under investigation and the necessary input data – especially concerning scenarios and weather data – are available.

Due to different boundary conditions, modeling approaches and parameter assumptions, energy system studies in general are hard to compare. This becomes obvious while analysing the resulting electricity system configuration from different studies for Germany as for instance in [1]. The installed power of storage technologies in 2050 varies from around 5 GW to 40 GW. The different assumptions in the underlying studies make it hard to identify and distinguish the different drivers for storage demand. Another example is investment costs for the used technologies. The studies employ different assumptions depending on several factors. Investment costs for pumped hydro for example vary in the range of 300 to 3700 €/kW and 1 to 1000 €/kWh [1]. The selection of technologies strongly depends on their costs if the usage and installed capacities are optimized endogenously in the models. As a result of these different assumptions studies are not comparable amongst each other.

A closer look at the modeling framework of several studies focussing on the German energy system shows further reasons for a low comparability. Table 1 presents important characteristics of the used models like time resolution and simulation period, European integration of the German power system, the grid modeling approach and the determination method of the installed power of fluctuating renewable energy sources (FRES) (wind and PV in Germany) and storage technologies. While some studies treat generation and storage capacity as exogenous[1] parameters that are varied [2–4], others optimize these values endogenously [5–7]. Also combinations of both are used [8,9]. All considered studies use a "copper plate" approach for the German grid and some optimize the power transfer capacities between European countries. Germany is either treated as an isolated electrical system or as part of a European electricity grid with either optimized or non-optimized transfer capacities. The time resolution of the models is one hour in all studies and all models besides DIMENSION [10] use a full year as simulation period. In DIMENSION, typical days are used describing representative system states like weekdays and weekend days in different seasons. This approach makes the evaluation of long time storage demand difficult [11]. The REMod-D model [12] is the only model optimizing the electricity and heat sectors together but does not consider a European integration. The REMix model is the only model optimizing FRES and other generation/flexibility technologies together on a European level. The Market Simulation model [13] and SimEE [14] both use an approach where the installed power of technologies is set exogenously while their operation mode is optimized endogenously. In [9] ELIAS is used for optimizing the technology mix whereas PowerFlex optimizes the operation mode of the exogenously defined (by ELIAS) technologies.

Each of these approaches has its own strengths and weaknesses and the results of the studies are of course valid relative to the assumptions made and under consideration of the restrictions of their models.

On an international level, a comprehensive model overview is given in [18–23]. Selected examples are summarized in Table 2. Similar to the findings for German energy scenarios and models, international modeling approaches also differ in many dimensions, as for example time resolution and the considered energy sectors.

In [31] the different models are grouped into energy system optimization models, energy system simulation models, power systems and electricity market models and qualitative and mixed-methods scenarios. Table 1 shows an example for each type. Our proposed method can be classified as an intermediate of a power system model and a mixed-methods scenario. We use a comprehensive meta-analysis of published energy scenarios of different kinds to identify key characteristics of a 2050 power system (see Section 2.2) together with a simplified power systems model yielding a cost-minimal mix of flexibility technologies (see Sections 2.4–2.6). Four key modeling challenges are also given in [31],. These are addressed with our proposed method as follows:

1. Resolving details in time and space

Especially for high shares of fluctuating renewables, a high resolution in time and space is necessary [32]. We are using an hourly time resolution for one year (8760 time steps), with wind data from more than 70 measuring stations and solar data for PV from 18 representative locations in Germany.

2. Uncertainty and transparency

Comprehensive expert knowledge is used to create a common basis for our evaluations. In 10 sub-working groups around 100

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[1] Exogenous parameters are not optimized within the model but set externally. In contrast, endogenous parameters are optimized within the model.