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Representing node-internal transmission and distribution grids in energy system models

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A B S T R A C T

Today's energy system models calculate power flows between simplified nodes representing transmission and distribution grid of a region or a country – so called copper plates. Such nodes are often restricted to a few tens thus the grid is not well represented or totally neglected in the whole energy system analysis due to limited computational performance using such models. Here we introduce our new methodology of node-internal grid calculation representing the electricity grid in cost values based on strong correlations between peak load, grid cost and feed-in share of wind and photovoltaic capacity. We validate in our case study this approach using a 491 node model for Germany. This examination area is modelled as enclosed energy system to calculate the grid in a 100% renewable energy system in 2050 enabling maximum grid expansion. Our grid model facilitates grid expansion cost and reduces computational effort. The quantification of the German electricity grid show that the grid makes up to 12% of total system cost equivalent up to 12 billion € per year.

1. Introduction

Energy system models are todays methods to calculate and optimize future energy systems often with the target function of minimal system cost (REMix, PLEXOS, TIMES, ReEDS, etc. [1]). One major barrier of such numerical calculation methods is the complexity of the model. A higher spatial granularity often increases the computing capacity and calculation time exponentially. However, reducing spatial resolution does not lead to more robust results when neglecting effects like grid expansion especially with high shares of fluctuating renewable energies like photovoltaics (PV) and wind turbines. Neglecting grid cost means that in a model node (continent, country or region) an ideal exchange of power flows is possible without any transmission constraint – the so called copper plate. This obviously leads to wrong system cost and a distorted power plant structure. Interconnecting model nodes using transmission links is a first step to solve the problem but computing capacity quickly reaches its limit when spatial resolution and the number of interconnection paths rise. Such transmission models are used e.g. in renewable energy-based power supply scenarios for Europe [2]. The logical solution quantifying the grid would be a simplified grid model which considers basic grid expansion effects inside a model node – a node-internal grid model. This paper is part of the dissertation "The Value of Concentrating Solar Power for a Sustainable Electricity Supply in Europe, Middle East and North Africa" http://elib.dlr.de/114683/.

1.1. State of science

Besides that mentioned characteristic of unlimited transmission in a copper plate – a copper plate has also spatial modelling restrictions regarding the power plant structure. For example a one node model means that the whole energy system with its production and demand is concentrated to one point. For renewable energies this characteristic is approached by weather data based time series consider the spatial expansion of the model geographical examination area. This raises of course the problem of calculating with spatial average time series which may overestimate the capability of renewable energies due to their often fluctuating resource even when calculating with hourly resolution. Effects on spatial and temporal resolution like clustering possibilities or cost differences, have already been analysed in Refs. [3, 4],

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by aggregating grid nodes or load profiles and in Ref. [5] with different time slices. The authors found out that a clustering can represent the grid and that higher temporal resolution leads to higher system cost. Effects on spatial resolution with high renewable energy supply up to 100% are rather rare and therefore grid effects are not well quantified.

Existing grid studies are focused on system integration costs for wind turbines. The assumed technological grid cost for wind turbines according to their capacity show huge bandwidths (0–1500$/MW) [6]. However these cost assumptions do often not consider technologies integrated in the energy system but try to quantify separately additional cost for technologies. The essential point is getting to know how much grid is needed in a cost efficient interplay of technologies. This means that such studies do not relate the grid to the simultaneous feed-in power of the energy mix. Therefore it is necessary to calculate the grid as one technological element in concurrence with other technologies in a temporal and spatial dissolved energy system optimization model. Schaber et al. [7] analysed transmission grid integration cost for wind turbines and PV over Europe in this manner, however in a relative low spatial resolution. They found out that the right wind/PV share reduces cost, power plant capacity and curtailment. Boie et al. [8] quantified grid expansion over Europe and North Africa using three different modelling tools with different temporal and spatial resolution. With new grid data [9, 10], it is now possible to quantify the transmission and distribution grid in a high spatial resolution using one energy system model.

1.2. Novelty and scientific contribution

1.2.1. Grid

Here we introduce our node-internal grid model and validate expansion cost assumptions in relation to wind and PV for Germany with an energy system model. This novel approach allows a quantification of grid cost as a function of feed-in power of wind and PV in a single copper plate integrating spatial transmission and distribution of the electricity grid. With this novelty it is possible to calculate a fictitious grid in a single model node reducing the number of model nodes and transmission paths and therefore computing resources. The methodological approach and the validation of the node-internal grid model is the core of the present paper. Other novel frame conditions of modelling constraints are discussed in the following but are not the nub of the matter because the investigation at hand is part of a broad system analysis.

1.2.2. Energy system modelling

The energy system analysis is based on the scenario year 2050 for Germany with a 100% renewable energy supply. A 100% renewable energy share is used to quantify the grid expansion in a large expansion potential. With an energy share variation of **fluctuating renewable** energies like *photovoltaics and wind turbines (and run-of-river)* and **dispatchable renewable** energies such as *biomass, geothermal power, gas turbines using renewable fuel and concentrated solar power (CSP) with thermal storage and co-firing* it is possible to examine grid expansion as a function of fluctuating energy share. Fluctuating renewable energy are assessed to be the dominant grid expansion drivers due to their potentially high surpluses. Cost sensitivity analysis (max, mean and min) show the scope of the grid cost range with overhead lines (OHL) and underground cables (UGC). A broad bandwidth of grid expansion configurations lead to a more general examination of grid cost as well of the examination of cost uncertainty. The used modelling constraints thus allow an assessment of the grid using high shares of fluctuating renewable energies.

2. Methodology and key assumptions

2.1. Energy system model REMix

As numerical energy system model we use REMix (sustainable Renewable Energy Mix) [2]. This bottom-up model has the target function of minimizing system cost using linear programming under perfect foresight. System cost includes the annuities of investment and the cost of operation and maintenance for energy relevant technologies (power plants, storage and transmission). The model can optimize capacities and dispatch based on the cost of technologies starting from a greenfield (model endogenous optimization), a partial greenfield (model endogenous optimization under exogenously given capacities). Furthermore a sole dispatch optimization with only exogenously given capacities is possible. REMix is built in the algebraic language GAMS using the CPLEX solver. As input data REMix uses weather data which are calculated by EnDaT (Energy Data Tool) to potentials and technological time series for renewable energies. With the least-cost optimization REMix produces as output data: cost, capacity and energy balance as well as emission data. A detail overview of the model methods is available in references [11, 2, 12].

2.2. Grid modelling

This chapter deals with the question of how to model the grid in a simplified way considering the major grid expansion effects (hypothesis). Secondly we show the validation methods of the modelling assumption.

2.2.1. Hypothesis

The fundamental idea of the model is that fluctuating renewable energy generates surpluses which lead to grid expansion. We illustrate in Fig. 1 and in Eqs. (1)–(5) the general functionality of our new node-internal grid model with a simplified power dispatch. Variables are listed in bold. Eq. (1) describes the generated power $\boldsymbol{P}_{gen}(t)$ and curtailed power $\boldsymbol{P}_{curt}(t)$ dependent on the existing and added capacity $P_{existCap}$ and $\boldsymbol{P}_{addedCap}$ multiplied with a normalized time series $s_{gen}(t)$ from REMix-EnDaT [2].

$$\boldsymbol{P}_{gen}(t) + \boldsymbol{P}_{curtail}(t) \overset{!}{=} \left(\boldsymbol{P}_{addedCap} + P_{existCap}\right) \times s_{gen}(t)\ \forall t \quad (1)$$

$$\boldsymbol{P}_{gen}(t) \le \boldsymbol{P}_{fluc\ feed-in,\ max}\ \forall t \quad (2)$$

While the existing grid is able to handle with a certain amount

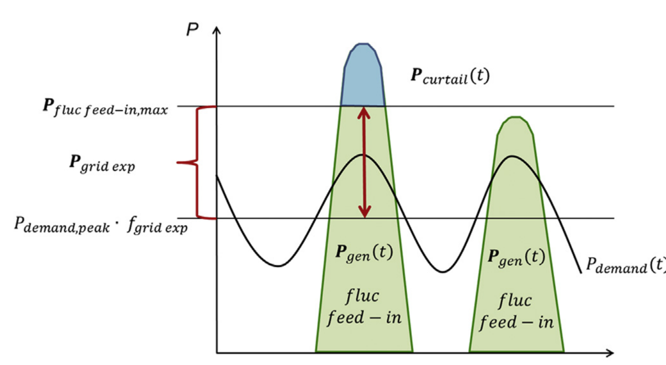

Fig. 1. Principle of the node-internal grid calculation model. Grid extension is related to feed-in power of fluctuating energies depending on a starting point in relation to peak load.