Interactions of flexibility demand and flexibility provision in a multi-coupled energy system with high shares of renewable energy

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Overview

To reduce carbon emissions, the transformation of the energy system will likely be based on a strong expansion of variable renewable energy sources (vRES), namely wind and photovoltaic (PV). Since the future expansion pathway is not only influenced by further cost reductions but also by emerging challenges like land-use and public acceptance, the long-term share of wind and PV in the vRES generation is uncertain. However, these two technologies differ significantly in their electricity generation characteristics, thus induce different flexibility needs to balance electricity supply and demand. In a power system with high shares of vRES, a higher (or lower) wind- (or PV-) share therefore influences the optimal combination of various available flexible technologies, including power plants, electricity grids, storages, demand-side-management (DSM) or sector coupling technologies.

Additionally to the vRES expansion, sector coupling offers the potential to decrease carbon emissions not only in the electricity sector but in further energy demand sectors. Although the ecological impacts of vRES-based electrification of the heating, transport and industry sector is obvious, the economic efficiency is often (not yet) conceivable. Assuming a energy-policy driven sector coupling, the configuration of a multi-coupled energy system further influences the mix of flexibility options required to integrate high shares of vRES.

The present contribution takes the two described development trends as basis for a two-dimensional scenario framework to analyse the interactions of different Wind-PV share scenarios with different approaches for sector coupling. This is done by applying two optimization models, on the one side for the vRES expansion and on the other side for the identification of optimal capacity and dispatch decision for flexibility options. Thus, additionally to the strived insights regarding the influence of varying Wind-PV shares on the flexibility needs of a transnational European energy system, the objective is furthermore to emphasise the impact of sector coupling on the optimal flexibility provision in the electricity market.

Methods

Regarding the first scenario dimension, varying wind-shares in the total vRES generation are assumed for the analysis of the flexibility demand scenarios. Overall vRES share is set to be 80 % of the current electricity generation of 17 European countries. Based on temporarily and spatially highly resolved weather data as input parameter, a vRES expansion model for the observed region is developed and the scenario-specific flexibility demand is analysed. Furthermore, for the second scenario dimension, the existing Electricity Transhipment Model (ELTRAMOD) is adapted for the present analysis and extended by a broad range of flexibility options. This includes several electricity generation technologies as well as export/import capacities, different storage types and DSM processes, and selected sector coupling technologies, namely heat pumps, battery-electric vehicles (BEV) and electrolyser for industry’s hydrogen demand. While the electricity sector is implemented in a bottom-up approach with high techno-economical detail, the selected energy demand sectors are included by a simplified representation including benchmark processes as competiting technologies. The sector coupling approach is implemented with different degrees of flexibility of the Power-to-X technologies. Within the model formulation an increasing flexibility in sector coupling, allows for the use of energy storages (heat storages, batteries of EVs and hydrogen storages) to decouple the electrification of the energy end-use sectors from the electricity market.

Results

The availability and simultaneity of the wind and PV based electricity generation strongly influences the flexibility needs in both, single countries as well as across the countries observed. Due to the day-night rhythm of PV-based electricity generation as well as a higher spatial correlation, the flexibility needs in terms of residual load parameters increase with higher PV shares in the vRES generation. These characteristics have an impact on the optimal provision of flexibility. While for scenarios with higher PV share, the role of storages to meet the aforementioned requirements is increasing, in scenario with higher wind shares this is true for electricity grids to spatially balance electricity surpluses and deficits. In general, with a more flexible sector coupling a substitution of electricity storages (e.g. batteries) towards alternative storages (e.g. heat storages) can be observed, mainly due to lower investment costs for the latter ones. In addition, energy storages in the observed energy demand sector allow for a more constant dispatch of the PtX technologies reducing the required respective peak capacities. An increase in the flexibility of sector coupling further decreases the need for electricity storages most significantly, with higher effects in scenarios with higher wind share. Other flexibility options are impacted to a lesser extent. Within the Power-to-X technologies, BEV have the highest influence on the results since the batteries in the EV cause no additional costs.

Conclusions

In a system perspective the present work underlines the requirement to holistically analyse the energy system transformation. With the inclusion of further energy end-use sectors, the objective to decarbonize the energy system can be more efficient in terms of total system costs and CO_2 reduction, since existing flexibility potential can be made available more economically. Within the present framework, the scenarios with higher PV shares require more flexible capacities and result in higher costs. Concluding, in a long-term perspective, the future vRES expansion pathway not only impacts the flexibility provision in the electricity market, but also the required technologies for a multi-coupled energy system.