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System dynamics within typical days of a high variable 2030 European power system

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ABSTRACT

The effect of variability in electricity generation on future high variable European power systems is a subject of extensive research within the current scientific literature. The common approach in these studies, regarding the assessment of the impact of the variability and related balancing assets, is by showing yearly aggregates (or longer) of results based on a variety of indicators. Although significant, these studies often lack in temporal details. This paper therefore focuses on the dynamics between load, generation, marginal cost and assets for balancing the generation variability, within a variety of typical days in a fully-integrated European power market. This is done by assessments of daily snapshots based on an hourly time resolution. The assessments underline the necessity of balancing assets, both during peaks as well as during lows in the output of variable generators. Interconnection capacity, electricity storage and demand response (DR) applications all contribute to renewables integration and to optimized utilization of cost-efficient generation capacity throughout the European power system. Important load flows from and towards load centers with high capacities of variable renewables are identified, as well as a significant role for transit countries with high interconnection capacities between these load centers. Despite the importance of electricity storage, it is shown that the traditional diurnal utilization of centralized electricity storage fleets becomes less viable with increasing penetration of variable renewables. A potential high CO2 price in the future European power market can become a determining factor in the system dynamics. Large price differentials in the merit order stimulate long distance flows as well as an increasing profitability for storage assets.

1. Introduction

In response to a changing climate and concerns regarding the availability of sufficient fossil fuel reserves [1], the member states of the European Union (EU) have set binding targets of respectively 20% [2] and 27% [3] of final energy consumption from renewables by 2020 and 2030 at the EU level. With a relative share of 21.9% of electricity in the final energy consumption of the EU in 2013 and considering an expected growth of electricity in the final energy consumption [4,5], a significant proportion of these targets must be achieved within the electricity sector. The growth potential of hydro power as current most mature renewable electricity source (RES-E) is fairly limited since the best locations are already in use [6]. RES-E with larger room of growth are solar photovoltaics (PV) and wind power. This is supported by impressive historical growth rates of on average 41% per year for solar-PV since 2000 and a growth rate of 15% in 2015 of worldwide installed wind capacity [7,8], as well as by realistic estimates for the potential of further increment of generation capacity [9,10].

An important characteristic of both wind power and solar-PV is that the generation of electricity occurs variably depending on the magnitude of solar radiation and wind intensity. At lower penetration levels of variable renewables (VRES), this variation can be compensated by dispatch of thermal power plants to secure the stability on the grid [11]. At higher penetration levels this becomes more difficult due to the non-dispatchable nature of VRES as well as the often-limited flexibility of thermal power plants [12]. To facilitate the integration of high capacities of VRES in power systems, a wide variety of methods for balancing the generation are being studied and applied. Examples are the improved flexibility of thermal power plants [13], better forecasting techniques for demand and generation [11,14], smart geographical placement of VRES [15], a variety of technologies for the storage of electricity [13,16], application of demand response (DR) assets

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[14,17–19] and increased interconnection capacities [20,21].

In the European context, a crucial step regarding the growing penetration of VRES would be the completion of a fully-integrated internal European energy market where electricity can flow freely between all countries [2]. The free flow of electricity would stimulate cost-efficient electricity generation by using generation technologies with the lowest marginal cost across Europe. Secondly, due to the generally low marginal cost of solar-PV and wind power, the growth potential for these systems would become even higher in an integrated market. Although in the past the progress towards the integrated market has been delayed [22], significant developments have been accomplished such as the coupling of the day-ahead market and the increase of HVDC interconnection capacity [23].

2. Literature review

Considering the expected development of the European power system in the direction of a more variable nature of generation, a range of studies have been conducted regarding the implications on the European scale and on the impact of possible methods for treating the variability within these high variable European power systems.

The biennially released 10-year network development plan (TYNDP) of the European Network of Transmission System Operators for Electricity (ENTSO-E) [24,25] showcases the necessity of on average a doubling in interconnection capacity by 2030, to facilitate the growing integration of VRES and to optimally utilize the available generation capacity within the European power system. A range of projected development visions are simulated in a variety of market modelling tools, including PowerSYM [26]. The impact of the different visions, including deviating assumptions on balancing assets and power market integration, are assessed through a variety of indicators such as national generation profiles, CO2 emissions, power exchange and differences in marginal cost. Results are separated per country, yet aggregated per year. The ENTSO-E TYNDP projections are expected to inform policy development and decision-making in the EU, at both the European Commission (EC) and in individual Member States.

The 2030 power perspectives study is constructed as an intermediate step towards the EU energy roadmap 2050 [27]. It provides a view on the progress needed by 2030 to be able to achieve the goals set in the EU energy roadmap 2050. It includes a technical assessment of the EU power grid and the impact of certain key elements such as DR, sharing of spinning reserves and incremental transmission capacities. Simulations of the European power system are conducted in the PRIMES model [28] with yearly aggregated output of results. The study highlights the importance of a diverse and compatible portfolio of low-carbon generation technologies across Europe and confirms the necessity of investments in interconnection capacity. Demand-side resources such as demand response assets and energy efficiency are indicated as an attractive mean to reduce the required investments in large-scale generation and interconnection capacity.

Gils et al. [29,30]. and Scholz et al. [30] present REMix, an energy systems model used to assess capacity expansion and hourly dispatch at various levels of solar-PV and wind power penetration. The studies assess the impact of increasing shares of VRES on the power system of Europe, with high temporal and spatial resolution. The studies are, however, not focused on the role of cross-border interconnectors. Deane et al. [31] present an integrated gas and electricity model of the EU energy system to examine supply interruptions. The model includes all 28 EU Member States and uses an hourly resolution. The focus of the study is the impact of interruptions in gas supply and storage on the energy system as a whole. A study by Qadrdan et al. [32]. introduces CGEN + to assess the role of DR as a source of flexibility in the EU's power system. Other sources of flexibility, such as large-scale storage and cross-border interconnectors, are not considered in similar detail and the model is limited to the case of Great Britain.

Energynautics GmbH has performed a European grid study for 2030 and 2050 [33]. The authors used grid optimization software ENAplan [34] to perform hourly dispatch simulations and assessed multiple scenarios with varying assumptions regarding priority dispatch for RES-E, DR integration, electricity storage, flexibility of conventional power plants and interconnection capacities. The study shows the importance of priority dispatch for RES-E between zones to minimize renewable curtailment. It also shows the potential of demand response for renewables integration. Not only does it underline the significance of load shifting from peak to off-peak hours, it also indicates that a shift of load towards times of peaks in high variable generation can lower the need for interconnection capacity. French electricity company Électricité de France (EDF) has performed a technical and economic analysis of the 2030 European power system with a 60% share of generated electricity from RES-E [35]. It includes aggregated results based on hourly dispatch simulations from the Continental model [36]. The study among others assesses the role of base-load and peak-load generators in a system with a high share of VRES. Important conclusion from the study is that storage and demand response can contribute to required flexibility in balancing supply and demand, but do not replace the need for backup generation.

The effect of variability in generation and the potential impact of balancing assets in the 2030 European power system have been extensively explored and quantified in the existing literature. Yet, the general approach in the presentation of results in these studies is by showing yearly aggregates and therefore often lack in temporal details. In this paper we will break away from this common method and focus on daily snapshots for a variety of representative days. The aim is to get a better understanding of what a typical day of electricity generation and consumption by 2030 in a high variable generating environment could potentially look like. This will include an analysis of the role of three main assets for balancing the variability, being centralized electricity storage, DR applications and cross-border electricity transmission. The specific interest of this study is more on the dynamics in the relation between generation, load, balancing assets and the marginal cost of electricity generation in different situations in the European context, rather than exact quantification of factors on the long term. By focusing on the dynamics at hourly resolution, this study attempts to provide additional insights on the high RES-E visions of the ENTSO-E regarding the 2030 European power system, as put forward within their Ten-Year Network Development Plan (TYNDP) [25].

3. Methodology

3.1. Artelys Crystal Super Grid

To simulate the operations of the European power system with realistic decision-making functionalities, a dispatch model has been used with an hourly time resolution. This high resolution is required for studying the integration of RES-E and associated flexibility assets. The specific software selected for this study is Artelys Crystal Super Grid. The model performs simulations of the European power system at country level on hourly basis by optimizing the utilization of generating units, electricity storage and cross-border transmission, while considering technical constraints. The optimization occurs by securing a supply of electricity with the overall lowest costs within a user-defined sliding time horizon. Fig. 1 shows an exemplary representation of hourly cross-border load flows from and to Italy during a summer day and night as visualized within the Artelys Crystal Super Grid software.

3.2. Construction of the 2030 European power system

The simulation of potential high variable European power systems within this study are based on the TYNDP 2016 [25], providing additional insights on the implications of the high RES-E visions within the projected range of the ENTSO-E. Per vision, the study includes country-specific installed generating capacities, interconnection capacities,