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Large-scale integration of renewable energies and impact on storage demand in a European renewable power system of 2050—Sensitivity study

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ABSTRACT

Driven by decreasing prices for photovoltaic (PV) systems and incentive programs of different governments, almost 100 GW of PV and over 100 GW of wind turbines (WT) have been integrated in the European power system by 2014. In some areas, the electricity generation already exceeds the demand, curtailing generation or pushing the existing power transmission infrastructure to its limits in certain hours. In order to reach the European Commission's targets for 2050, the integration of renewable energies will require flexibility sources, independent of conventional generation, in order to provide standard security of supply. Together different flexibility sources will ensure the match between demand and supply at any given time. Energy storage systems can provide this flexibility by shifting the load temporally while transmission grids provide the shift of load spatially. Up to a certain extent, transmission capacity and storage capacity can replace each other, i.e. storage can reduce the load on transmission infrastructure by mitigating local peaks in load and/or generation. For the transition to a fully renewable energy system by 2050, major changes have to be achieved in the structure of the power system. The planning tool GENESYS is a holistic approach that optimises the allocation and size of different generation technologies, storage systems and transnational transmission corridors of a European power system. The source code for the mentioned tool is available free of charge under LGPL license. It can be freely parameterized by the user which allows the study of different power systems under individual assumptions with regard to load, generation potential and cost of the different system components. This publication will give an introduction to the planning methodology, the system model and the optimisation approach. Optimisation results obtained with GENESYS for a fully renewable electricity system for Europe and a cost structure expected for 2050 will be presented together with sensitivity analyses investigating main assumptions. Outcomes show the optimal allocation of PV and WT in a European power system, the resulting demand for storage capacities of different technologies and the capacity of the overlay grid.

1. Introduction

Since the European Commission presented target values for greenhouse gas emissions [1], the evolution of the current power system was characterised by the extensive integration of various renewable energy sources. Until 2013 total installed capacities of 117 GW wind power generators and around 78 GW PV generators have been installed into the current European power system [2]. The integration process is still ongoing, driven by decreasing PV cost, for instance on rooftops. It can be characterised as unplanned and initiated by individual persons and companies, which leads to a strongly decentralised organisation of generation. In addition, the energy feed-in from offshore wind parks and onshore parks in coastal regions cause a major challenge for transmission system operators in periods of strong wind due to high power fluctuations.

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To counter this, they have developed a ten year development plan [3] for the expansion of the transmission capacities in the European grid.

1.1. previous research in power system modelling

The field of power system modelling is addressed by various different approaches, which were compared and analysed in [4],[5] but the total number of existing models can only be estimated to grow constantly. The most general difference is the limit of each model, for example the power sector of the energy system is the limit in the presented work, while other models support multiple sectors and their interactions. Some models focus on market models; those are not in the centre of this work. The second category is motivated to investigate the total generation and its cost without market effects. There are fundamental differences in the investigated geographical scale e.g. island, national, multi-national, continental, and worldwide. The spatial resolution ranges from a 'copper plate' without internal structure to high spatial resolutions of few km^2 and a detailed grid. To contain the complexity each model has limitations in the spatial or temporal resolution, depending on the investigated subject. Therefore some models only investigate typical days, weeks or months, while others calculate the state of the power system in time series of 15 min, 1 h or 3 h. The simplest approach which is applied in [6] and [7] investigates the necessary balancing energy which results from utilisation of volatile PV/Wind power of different ratios. Other models can be categorized as system "integrated assessment models", "operation models" or "hybrid approaches" [8]. Our model is part of the latter category and incorporates a Greenfield investment approach in 21 interconnected regions with a hierarchical dispatch of system components operating on hourly time series [9], [10].

The presented tool can, amongst others, give an outlook regarding the future needs for grid expansion and integration of storage units in case of high penetration of intermittent renewable generators by 2050. The methodology of this tool is explained in detail in [11], which is briefly summed up in the next section. In this work, the configuration of a future 100% renewable power system considers PV and WT as generation units and batteries, pumped hydro (PH) and hydrogen storage as available short, medium and long term storage systems respectively. Supplementary, a high voltage direct current (HVDC) overlay grid is included for energy transport. The investigated components will become major sources of flexibility, which is a requirement to guarantee system stability.

The fluctuating nature of the non dispatchable generators wind and PV leads to a temporal and spatial mismatch between generation and demand. Spatial flexibility in the power sector can be delivered by transmission grids as stated in the following subsection. The temporal flexibility can be delivered by various energy storage technologies, which can be divided in the categories mechanical storage, electro-chemical storage and electrical storage. The centre of interest of this analysis is to identify the demand for temporal flexibility on a temporal scale, the technologies are chosen accordingly, which means one technology of each temporal category is selected. We pick batteries for the high frequency fluctuations of few hours, because of high efficiency and relatively high price for energy, but low cost for power. It is intended to balance the day cycle of PV generation. Batteries are used already today for grid support, peak shaving and ancillary services, and are foreseen to become more important e.g. with electric vehicles, and PV solar home system integrations. The same category of services could be delivered by flywheels, super-capacitors or superconducting magnetic energy storage to a certain limit. Historically PH storage plays an important role for power management and compensation of demand fluctuations of the day cycle, for future applications it can have the function of flexibility on a medium time scale of a few days, because of competitive energy cost compared to batteries. An alternative, but less mature technology can be the advanced adiabatic compressed air energy storage (AA-CAES) or vanadium redox flow battery systems. The efficiency in this category needs to be quite high with a medium price for the energy. In systems with no alternative backup capacities the mismatch between generation and demand amounts to about 12–15% [6] and up to 24% [7] annual consumption, which needs large energy reservoirs (TWh scale) with a long time scale in the order of months for discharging. Most promising technology is hydrogen electrolysis, with storage of gas in large caverns or other reservoirs (Power-to-Gas), which would also have an optional connection to gas transmission systems or utilisation in the transport sector. The cycle with re-conversion through hydrogen turbines, or combined cycle gas turbines offers only limited efficiency, but low cost for energy storage. Alternative technologies with similar characteristics can be the methane generation or the rather conceptual hydraulic rock storage.

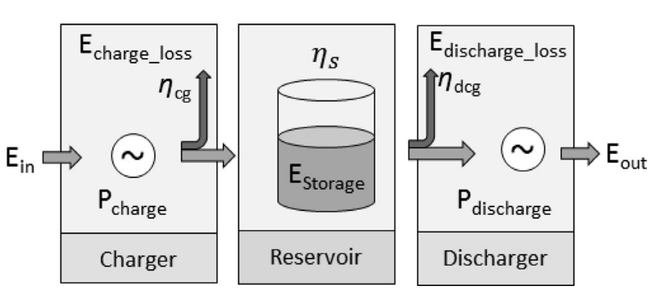

Fig. 1. Model of the storage system components.

Another alternative of backup capacities are renewable sources based dispatchable generation from biomass and waste, which is limited in the annual energy amount, and conventional power plants from fossil fuels, in case limited CO_2 emissions are allowed, and nuclear power. The electricity demand in the presented approach is fixed, but also demand flexibility from demand side management (DSM) is imaginable. Whichever alternative is available has results in a reduction of the long term storage demand, which was shown by [12] and [6].

The developed planning tool makes use of the Covariant Matrix Adaption-Evolution Strategy (CMA-ES) developed by N. Hansen [13] in order to optimise the dimensioning and allocation of the above mentioned components of the future European power system. In several works [14], [15], a linear programming (LP) approach is applied to determine the optimal unit commitment and thus the operational costs of a future power system. However, the problem complexity often sets limits for the simulation timeframe, and thus especially long term storages (capable of providing energy at full load for several weeks) can only be run under certain limits. In order to avoid this complexity, in this work the system operation is calculated by a hierarchical management, which is able to efficiently operate generation and storage units of different technologies over periods of several years without perfect foresight of the future situations. The developed methodology will also provide a closer insight into the program's sensitivities concerning the mix of available technologies and technology cost variations.

1.2. Previous results relevant to the current work

Previous studies confirm that dependent on the system configuration, there exists an optimal mix of wind and PV for renewable electricity generation. The investigation in [16] analyses