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On the optimal mix of wind and solar generation in the future Chinese power system

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ABSTRACT

China is one of the largest and fastest growing economies in the world. Until now, the corresponding growth of electricity consumption has been mainly provided by coal. However, as national reserves are limited and since burning coal leads to severe environmental problems, the employment of alternative sources of energy supply has become an important part of the Chinese energy policy. Recent studies show that wind energy alone could meet all of China's electricity demand. While our results validate these findings with regard to annual production, we look at the hour-by-hour resolution and uncover a major limitation: wind generation will not match the demand at every given point in time. This results in significant periods with over- and undersupply. Our study shows that combining wind and solar generation in the power system reduces overproduction significantly and increases the capacity credit of the combined VRE (variable renewable energy sources). The article demonstrates that up to 70% of VRE comprising 20–30% solar generation in the form of photovoltaics (PV) can be integrated into China's electricity system with moderate storage requirements. We encourage planners to consider those findings in their long-term planning in order to set up a sustainable power system for China at low costs.

1. Motivation and related work

China's electricity consumption has been characterized by a steady growth since the 1990s as reflected by annual generation depicted in Fig. 1. In 2012, Chinese electricity consumption already reached 4960 TWh/a which is more than that of the entire European Union [1]. Between 1990 and 2012, China's electricity consumption has grown almost 8% per annum [2]. Future electricity consumption is predicted to increase to almost 10 PWh/a in 2030 [3]. Coal is currently the major source of electricity generation, providing approximately 80% of China's electricity in 2012. This heavy deployment leads to serious environmental problems both locally in the form of air pollution (see e.g. Refs. [4,5]) and globally through tremendous amounts of CO_2 emissions [6].

The second most important energy source for China is hydropower which accounted for more than 10% of generation in 2012. A further extension of hydropower is planned for the upcoming years, however, potentials are limited [7]. In order to be able to serve the rising demand, other sources are being explored – the most promising ones being wind and solar in form of PV (photovoltaics). The total installed wind and PV power capacity in 2012 was 61 GW and 3.4 GW respectively, producing 4.1 TWh in total, which is still less than 0.1% of total generation [8]. This shows the small role that wind and PV currently play in the Chinese electricity market. Even though Tianyu et al. [9] showed that VRE (variable renewable energy sources) integration alone will not solve China's environmental problems as emission leakage to other sectors might occur, VRE growth is fast and potentials are huge. Renewable energy is an important part of the current policy and targets are discussed in the Chinese 5-year plans [10]. The deployment of VRE is seen as one of the most important measures to overcome the environmental problems mentioned before.

Recent research from the Harvard China Project [11] even showed that China could be entirely powered by electricity generated from wind turbines. A detailed potential study using GIS (Geographic Information System) and wind speed data from NASA (National Aeronautics and Space Administration) was conducted herein, leading to the conclusion that huge amounts of wind energy should be used in a future system. The authors found that costs for wind energy installations are only slightly higher than a further

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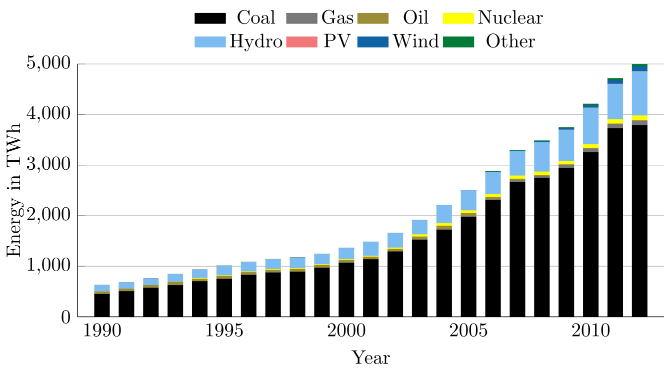

Fig. 1. Development of electricity generation in China from 1990 to 2012 [2].

extension of coal power while leading to dramatic reductions in CO_2 emissions. The study, however, focused on an annual production and consumption and did not consider the challenges with continuously matching demand and supply – we contribute to this research gap by providing an hour-by-hour analysis.

On an hour-by-hour basis, additional problems with the integration of wind generation arise. Backup power is required for times with lower wind speeds, transmission has to be built in order to transport electricity from the generation sites to the demand centers, and storage is needed to balance fluctuations. The lack of such infrastructure is already becoming a concern even with current wind installations and will develop to more dramatic consequences in the future (see also [12,13]). Here, we contribute by quantifying the required back-up and storage capacity for different scenarios.

In Ref. [14], potentials and optimal configurations of offshore wind power sites were explored. The study suggested that mixing different locations will lead to a smoothing in wind generation and thus to a more steady electricity supply. Our study extends this research by considering PV as a complementary source to wind energy. Balancing effects that were found for spatial combinations of offshore wind farms can also be found for the combination of different sources – wind and PV – in a future power system. Research in that direction was already conducted for Europe suggesting that such a combination is beneficial for energy considerations ([15] or [16]) and also for flexibility requirements [17]. Another reason for this co-analysis is the recent growth of PV installations and the dramatic fall in prices that was observed. Investment costs of PV modules fell from $10/W in the early 90's to less than $2/W in 2011; a significant further decrease is predicted [18]. This might lead to a situation with PV generation having costs that are equal or below that of wind power in many world regions [19]. Currently, however, wind and PV are not competitive in China and require some form of support like feed-in-tariffs [20,9]. In Ref. [21], the authors showed that wind power will be cost-efficient, even compared to coal power, as soon as external costs are internalized in the system by a CO_2 price of $50/t. Zhang et al. [37] applied a computable general equilibrium (CGE) model to analyze the current feed-in tariff policies and find that the economic potential of wind energy exceeds the targets of 400 TWh for the year 2020 which shows the chances lying ahead for the technology.

In Ref. [22], scenarios of future power supply in China with up to 300 GW of wind and 300 GW of PV installations were investigated. The results showed that oversupply of renewable generation will occur in certain hours even though the contribution to the annual electricity generation is still below 25%. As a consequence, flexibility provided by storage or DSM (demand-side-management) will be required to integrate more renewable generation, which was examined for China e.g. by Chang et al. [23]. In order to keep integration costs at a low level, it seems beneficial to find a mix between wind and PV that minimizes the hourly oversupply while reducing the peak power and the annual generation of remaining conventional sources. The research for such a mix is the major contribution and content of this paper.

The paper is organized as follows: After a short introduction, Section 2 explains the dataset we use and how the residual load for the scenarios is constructed. In Section 3, the results are presented for our evaluation measures, followed by a discussion about the optimal mix in Section 4. Finally, we present a conclusion in Section 5 which includes remarks on policy implications.

2. Scenarios for the residual load – method

This chapter describes the method applied for constructing residual loads. First of all, we introduce the dataset that was used to derive generation patterns, followed by an estimation of available resource potentials. A demand pattern for each region is modeled and, based on that, scenarios for China's residual load in 2030 are developed.

2.1. Hourly wind and PV generation

The basis of our analysis is geographically-spread time series data for wind and PV production as well as for demand in an hourly resolution. We consider separate time series for each Chinese province as generation and demand characteristics differ strongly from region to region. Time series data for wind and solar generation is based on NASA reanalysis data [24], which consists of hourly values of wind speed and solar irradiance at a spatial resolution of 0.5 E/W and 0.66 N/S for the whole world. The weather data for each spatial grid cell was converted by Janker [25] into normalized hourly wind and PV generation. A weighted average was built from the time series in the individual grid cells in order to obtain aggregated power production for each province. The weighting factor for each cell is proportional to the resource potential in terms of wind speeds or solar radiation (energy density) – more capacity is assumed to be installed on sites with higher energy density as this is cost-efficient. Resulting FLH (full load hours) for wind and PV in the regions are depicted in Fig. 2 and detailed data is given in Appendix A.1. Both the annual FLH [25] and generation gradients [17] were validated in a European context and are assumed to be valid for China as well.

2.2. Potentials of wind and PV generation

As stated by Mc Elroy et al. [11], wind power could provide all of China's electricity supply in 2030, even with the projected growth of up to 10 PWh of electricity consumption per annum. We conduct a similar GIS analysis as in Mc Elroy et al. [11], but for both wind and PV potentials (onshore and open space utility-scale PV systems). The physical constraints in this analysis are land cover types and slope values. Land with other uses (e.g. cities and forests) as well as land that cannot be accessed (e.g. rocks, land nuder ice and snow, water) was excluded from considerations of available area. Furthermore, PV can only be installed in low-slope areas with grades less than 3% and wind turbines require areas with slopes below 20% [26].

The land area that would be suitable for wind power generation is calculated as 3.9 Mio. km^2, which results in a land-suitability factor of 0.4 compared to the total land area of 9.9 Mio. km^2. The land-suitability factor per province is depicted in Fig. 3 on the left. It varies regionally with a tendency toward lower suitability factors along the east coast.

Concerning the land suitability for PV, an area of 1.9 Mio. km^2 is identified as being appropriate, leading to a land suitability factor of 0.2. Reasons for this lower value are the stricter constraints on the