Energy 147 (2018) 534–546

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Cost-optimal design of a simplified highly renewable Chinese electricity network

Hailiang Liu*, Gorm Bruun Andresen, Martin Greiner

Department of Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000, Aarhus C, Denmark

ARTICLE INFO

Article history:
Received 26 June 2017
Received in revised form
11 January 2018
Accepted 12 January 2018
Available online 30 January 2018

Keywords:
Large-scale integration of renewables
Renewable energy networks
Wind power
Levelised cost of electricity
China

ABSTRACT

Rapid economic growth in China has lead to an increasing energy demand in the country. In combination with China's emission control and clean air initiatives, it has resulted in large-scale expansion of the leading renewable energy technologies, wind and solar power. Their intermittent nature and uneven geographic distribution, however, raises the question of how to best exploit them in a future sustainable electricity system, where their combined production may very well exceed that of all other technologies. It is well known that interconnecting distant regions provides more favorable production patterns from wind and solar. On the other hand, long-distance connections challenge traditional local energy autonomy. In this paper, the advantage of interconnecting the contiguous provinces of China is quantified. To this end, two different methodologies are introduced. The first aims at gradually increasing heterogeneity, that is non-local wind and solar power production, to minimize production costs without regard to the match between production and demand. The second method optimizes the trade-off between low cost production and high utility value of the energy. In both cases, the study of a 100% renewable Chinese electricity network is based on 8 years of high-resolution hourly time series of wind and solar power generation and electricity demand for each of the provinces. From the study we conclude that compared to a baseline design of homogeneously distributed renewable capacities, a heterogeneous network not only lowers capital investments but also reduces backup dispatches from thermal units. Installing more capacity in provinces like Inner Mongolia, Jiangsu, Hainan and north-western regions, heterogeneous layouts may lower the levelized cost of electricity (LCOE) by up to 27%, and reduce backup needs by up to 64%.

1. Introduction

China is undergoing tremendous challenges of decarbonization and air quality impairment due to rapid industrial growth, transportation expansion and sharply increased demands of electricity [1]. Coal as the main source of power is being changed, and the employment of alternative sources has become an important part of the Chinese energy policy. For many years, the only renewable energy source in China has been hydro, meeting 19% of annual electricity demand in 2014 [2]. But hydro is reaching its full potential due to site limitations. Wind and solar power, however, have become affordable [3] and more suitable for large scale expansion [4–6].

Considering the growing penetration of renewables, some scholars have looked into implications of integrating large amounts of wind and solar energy in the Chinese power sector. A combined source-grid-load planning model [7] was introduced to seek a cost-optimal solution at the macro level, taking into account higher renewable penetration up to 2030. They suggested striking a balance between resource-rich and high-load regions by means of a rapid expansion of the inter-regional transmission grid. The same is suggested by Ref. [8]. In this context, economic savings and better utilization of wind and solar power may be achieved by shifting renewable capacities towards resource-rich regions that are linked to regions with high demands by high-capacity transmission lines. In the studies, emphasis was given to policy target driven scenarios and system cost reductions were not explicitly discussed.

Both [7] and [8] studied the renewable integration using annual average values. This does not explicitly capture the variable nature of renewables. Ref. [9] is the first study to base the analysis on hourly data. The high temporal resolution allowed insights into backup, storage and flexibility needs. All three studies were

* Corresponding author.
E-mail address: HLL@eng.au.dk (H. Liu).

https://doi.org/10.1016/j.energy.2018.01.070
0360-5442/

Nomenclature

α_n	Share of average wind power generation in the wind-solar mix
β	Heterogeniety parameter in heuristic layouts
Δ_n	Mismatch between renewable generation and load
γ_n	Renewable penetration level
$\mathscr{K}^B$	Backup capacity
$\mathscr{K}^T$	Transmission capacity
$\mathscr{K}^S_n$	Solar power capacity
$\mathscr{K}^W_n$	Wind power capacity
B_n	Balancing
C_n	Curtailment
$CapEx$	Capital expenditure
CF^S_n	Solar power capacity factor
CF^W_n	Wind power capacity factor
d_l	Length of link l
E^B	Backup energy
F_l	Power flow in link l
G^B_n	Backup power generation
G^R_n	Renewable power generation
G^S_n	Solar power generation
G^W_n	Wind power generation
H_{ln}	Matrix of power transfer distribution factors between node n and link l
K	Heterogeniety parameter in optimized layouts
n	A province
$OpEx$	Operation expenditure
P_n	Injection pattern
r	rate of return
L_n	Load
$LCOE$	Levelized cost of electricity

concerned with China as a single aggregated entity, rather than a power system with inter-connecting provinces.

This paper is inspired by similar studies for large scale integration of wind and solar power in Europe [10,11], US [12,13] and Australia [14], where the analysis are implemented on a continental level, yet still with starting points of high spatial and temporal resolution wind-solar generation time series. As an emerging titan, the Chinese power sector is growing more and more renewable, but for lack of high resolution data, studies for this new regime has yet to appear. The present paper focuses on a simplified 100% renewable power system for the 31 contiguous provinces of China. Hourly time series of wind and solar power generation, as well as load covering eight years for each of the 31 provinces are generated and used in the analysis of the interconnected network, the structure of which is illustrated in Fig. 1. The time series are based on high quality weather data and have been validated to the extend that it was possible using state-of-the-art practices [15–17]. In our opinion, our primary addition to the literature is filling the gap with this unique validated high resolution dataset in the new domain and laying the ground work for other interested researchers.

The first part of the analysis consists of two ambitious baseline scenarios for the far future, in 2050, where the overall cost composition of the Chinese power system with a 100% wind-solar penetration is analyzed without and with an interconnecting transmission grid between the provinces. In the baseline scenarios all provinces have similar energy autonomy in the sense that the wind-solar penetration is fixed to 100% for each individual province.

To analyze the economical advantage of relocating wind and solar generators to more favorable locations, two additional scenarios are analyzed. The first of these is based on a heuristic, analogous to [19], where sites with better capacity factors, i.e. higher annual wind or solar yield, gradually produce a higher fraction of the total energy. However, this approach ignores the match between demand and generation, and may lead to relative high curtailment and balancing energy needs. This is taken into account in the second approach, where the total cost per MWh energy delivered to cover the demand is minimized by redistributing wind and solar capacity to favorable locations. The second approach is a trade-off between lowering the wind and solar energy production cost and maximizing the useful energy from these variable resources. It is achieved by selecting locations with high energy yields as well as production patterns that complement each other to provide a better match to the demand time series. Again, the method allows different degrees of heterogeneity as decision makers may want to factor in energy autonomy as well as cost optimization. The difference between the two approaches highlights the importance of taking into account correlations in highly renewable scenarios. Table 1 summaries the four scenarios considered throughout the paper, highlighting their differences.

This paper is organized as follows. Section 2 introduces hourly wind, solar and load time series as well as methods of quantifying backup and inter-regional transmission needs. Section 3 presents the homogeneous baseline scenarios. In Section 4 wind and solar generators are relocated to more favorable provinces using the two approaches to lower total system cost including backup units and transmission grid. Sensitivity analysis and the issue of curtailment is discussed in Section 5 before Section 6 concludes the paper.

2. Data and methods

A simplified model of the Chinese electricity network is used for the study. Here, each province is aggregated into a single node located at its geometric center, and the connecting links represent the combined transmission capacity between neighboring provinces. Fig. 1 shows the network topology and the average loads of the individual provinces.

The hourly renewable power generation in node n is composed of wind G^W_n and solar PV G^S_n generation:

$$G^R_n(t) = G^W_n(t) + G^S_n(t). \tag{1}$$

This renewable generation, shown in Fig. 2, is modeled using hourly weather data covering 2005–2012 with spatial resolution of 40×40 km^2. Details can be found in the supplementary material. The hourly load L_n time series modeling is also described there.

The penetration γ_n of renewable power generation for each node is defined as the ratio between average renewable generation, ignoring curtailment, and average load L_n:

$$\gamma_n = \frac{\langle G^R_n \rangle}{\langle L_n \rangle}. \tag{2}$$

Furthermore, the wind-solar mix $0 \leq \alpha_n \leq 1$ is defined as

$$\alpha_n = \frac{\langle G^W_n \rangle}{\langle G^R_n \rangle}. \tag{3}$$