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 met by coal power. 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 photovoltaics (PV) in the power system reduces overproduction significantly and increases the capacity credit of the combined variable renewable energy sources (VRE). The article demonstrates that up to 70% of VRE comprising 20-30% 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 electricity system for China at low costs.

1. Motivation and Related Work

China's energy consumption is characterized by a steady growth since the 1990s as depicted in Fig. 1. In 2012, Chinese electricity consumption already reached 4,960 TWh/a which is more than that of the whole 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. [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 - mainly wind and solar. 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. Furthermore, Tianyu et al. [9] showed that VRE integration alone will not solve China's environmental problems as emission leakage to other sectors might occur. However, growth is fast and potentials are huge; renewable energy is an important part of the current policy and targets are discussed in the 5-year plans [10]. The deployment of VRE is seen as one of the most important measures to overcome the environmental problems mentioned before.

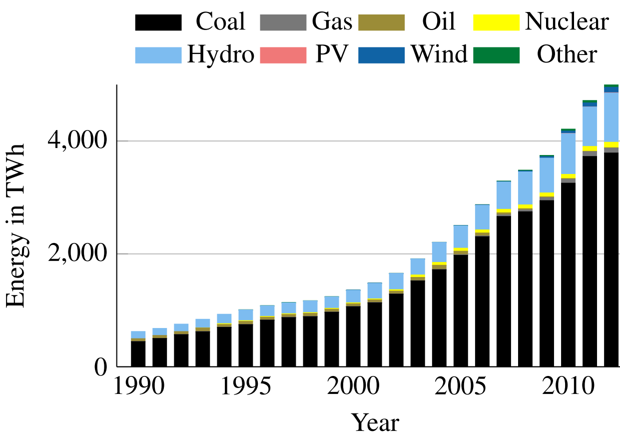

Figure 1: Development of electricity generation in China from 1990-2012 [2]

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 systems and wind speed data from NASA 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 extension of coal power while leading to dramatic reductions in CO_2 emissions. The study, however, focused on an

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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 [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 ([15] or [16]) for energy consideration 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 fall 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 [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.

In [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 hours with an 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 demand-side-management (DSM) will be required to integrate more renewable generation, which was examined for China 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 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 are geographically-spread time series data for wind and PV production as well as for demand in an hourly resolution. We define time series data for each Chinese province as generation and demand characteristics differ strongly from region to region. The time series data for wind and solar generation are 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 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 and 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 towards 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 constraints in this analysis are land-cover types and slope values. The following land-cover types are excluded: cities, farmland, forests, land under ice and snow, rocks, swamps, and water bodies. Beyond that, PV can only be installed in low-slope areas with grades less than 3% while this boundary is 20% for wind turbines [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 towards lower suitability factors along the whole east coast.

Concerning the land suitability for PV, an area of 1.9 Mio. km^2 was identified as being appropriate, leading to a land-suitability factor of 0.2. Reasons for this lower value are the stricter constraints on the slope of suitable land area. The geographic distribution of land-suitability factors for PV across provinces is similar to that of wind power: lower suitability on

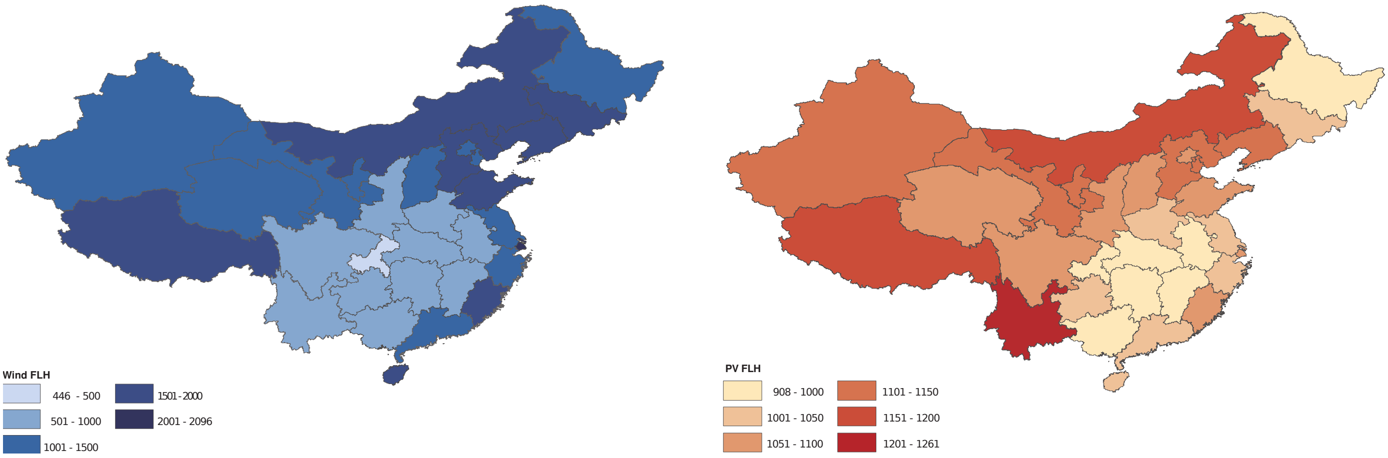

Figure 2: Generation full load hours for wind(left) and PV(right) in Chinese provinces

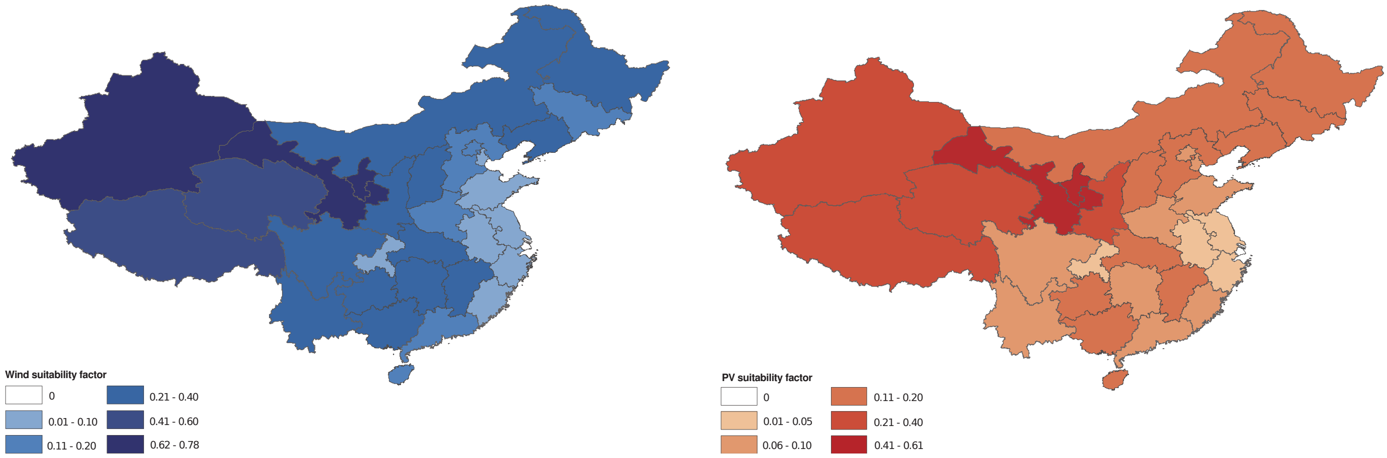

Figure 3: Land suitability factor for wind(left) and PV(right) generation in Chinese provinces

coastal areas. The land-suitability factor for PV is depicted in Fig. 3 on the right.

Based on the suitable land area, we compute generation potentials for China. Assuming power densities of 4.71 MW/km^2 for wind and 38.4 MW/km^2 for PV results in estimated technical potentials of 23.74 PWh/a and 81.96 PWh/a respectively. These wind and PV energy potentials are more than four times (wind) and 16 times (PV) the current electricity demand. Table A.1 in the appendix provides an overview of FLH and technical potential for each province and technology. The values confirm the results obtained by [11] for wind energy where the potential was estimated to be at 24.7 PWh. We aware that a larger percentage of PV will be installed on rooftops which is not included in this analysis. However, the potentials are so enormous and will not be a constraint anyway, hence, this fact can be ignored in our analysis.

2.3. Electricity Demand

Hourly electricity demand patterns were calculated based on the monthly, the weekly, and the daily pattern of demand for each region (see Fig. 4 for an example). For more details about the load modeling we refer to [22]. After determining the characteristic load curve, we scale those load curves to the projected demand levels for 2030 according to [27] for each province. Summing up all provinces, we assume a total annual electricity demand D of 10 PWh, which is the same assumption as in [11] and thus makes results comparable.

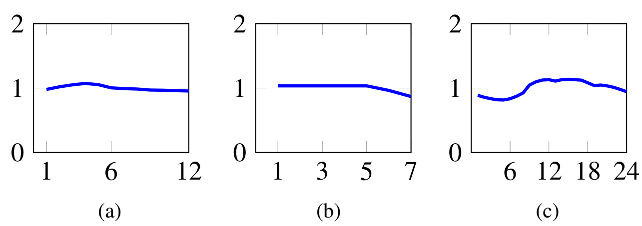

Figure 4: Illustration of the load model formulation: a) Month of the year, b) Day of the week, c) Hour of the day.

2.4. Scenario Development

Several scenarios about future VRE extensions are evaluated, i.e. scenarios including different VRE levels and different mixes among the applied technologies. VRE integration levels start off with 200 TWh (2% of projected demand) and reach up to 10 PWh with steps of 200 TWh. This leads to 50 levels of VRE integration. Ranging from a 100% wind energy (and no solar) to a 100% solar energy scenario. We gradually vary the percentage of both sources by 5% resulting in 21 different wind/solar mixes. Our overall set of scenarios $\mathcal{S}$ comprises 1050 scenarios.

2.5. Residual Load

For our analysis, we consider the residual load, which is defined as the demand minus the generation from wind and PV. The residual load is calculated for defined scenarios characterized by the percentage of renewable sources α (see Equation (1)) and the percentage of PV in the renewable generation β (see Equation (2)):

$$\alpha = \frac{\sum_{t=1}^{t=8760} P_{wind}(t) + \sum_{t=1}^{t=8760} P_{PV}(t)}{D} \tag{1}$$

$$\beta = \frac{\sum_{t=1}^{t=8760} P_{PV}(t)}{\sum_{t=1}^{t=8760} P_{wind}(t) + \sum_{t=1}^{t=8760} P_{PV}(t)} \tag{2}$$

where $P(t)$ is the hourly average power output which equals the hourly energy generation at time t and D is the annual demand.

2.6. Regional Distribution of Wind and PV Capacities

The scenarios vary in the installed capacities of wind and PV facilities. However, the question about the geographic distribution of those sources remains. The allocation of wind/PV to the regions j for each of the scenarios s is described by the factor w_j as defined in equation (3). This estimation of distribution considers both, the regional capacities of wind/PV in 2011 named C_j^{2011} that was published in [28], as well as the annual full load hours of each region $\mathrm{FLH_j}$. The full load hours are considered in order to value the quality of the resources and to apply scenarios that respect cost efficient planning. The factor w_j is calculated for wind and PV separately:

$$w_j = \frac{C_j^{2011} \cdot \mathrm{FLH}_j}{\sum_{j=1} C_j^{2011} \cdot \mathrm{FLH}_j}. \tag{3}$$

As the potential for each region is limited (see Table A.1 for details), the calculation has to be conducted iteratively. In a first round, all generation is distributed according to the factor w_j. All generation capacity that exceeds regional limits will than be divided amongst the remaining regions with the same approach. The procedure is carried out iteratively until all generation required for the scenario is placed in the regions; an identical approach is applied to solar energy. Table A.2 provides an overview of the required capacities in several major scenarios.

2.7. Other Renewable Generation: Hydro, Geothermal, Biomass

Currently, the major source of renewable energy in China is hydro generation (see Fig. 1). In the further analysis of this paper, hydro and any other technologies like geothermal and biomass are not considered; a fact that has to be explained. One reason is that further extensions of hydro generation is limited due to environmental concerns and geographic constraints [7]. Another and more important reason is that hydro generation as well as geothermal and biomass are not intermittent in a sense as wind and PV are. They are either almost constant sources of electricity generation or can be controlled. Including them, therefore, would scale our results to a system with lower residual load but would not change the structural outcomes and interpretations of our research.

3. Evaluation of Results

This chapter presents the major results of our analysis. We identify the capacity credit, the sum of negative loads, as well as the storage requirements as important characteristics for a power system with high shares of renewable energy sources. The ideas behind our metrics are illustrated in Fig. 5 which shows the annual duration curve of load and residual load. The capacity credit is the reduction of peak load by the generation from renewable sources (the value of the residual load at x=0). This amount of controllable generation capacity has to be available at any time in order to guarantee a resilient power system. There will be some reserve margin to this value and the measure has to be considered carefully; however, a reduction will lead to less deployment of expensive peak generation in any case. The green area shows the generation from VRE which leads to the remaining grey area that still has to be provided by conventional generation. The red area shows energy that is produced in the case of excess demand (negative residual load). The amount of energy is thus a first indicator of how much energy has to be curtailed in the absence of energy storage. The requirements for energy storage, however, depend on the hourly fluctuations and cannot be seen in Fig. 5 but are described in details in Section 3.3.

3.1. Capacity Credit

Our first measure is the capacity credit which defines the installed power of conventional generation that could be substituted by renewable energies. The capacity credit, as a measure for the positive effect of variable renewable energy sources, has to be considered carefully: there won't be a 100% guarantee for the credit as we consider only one year in our analysis, which does not account for any possible constellation of load and VRE generation. Additional generators have to be in place as an emergency reserve. Nevertheless, a higher capacity credit has positive effects on the power system costs as less generation from expensive peak generators is required [29]. A reduction of peak capacity is also a sign of a smoother residual load which leads to reduced system stress. The resulting capacity credit for

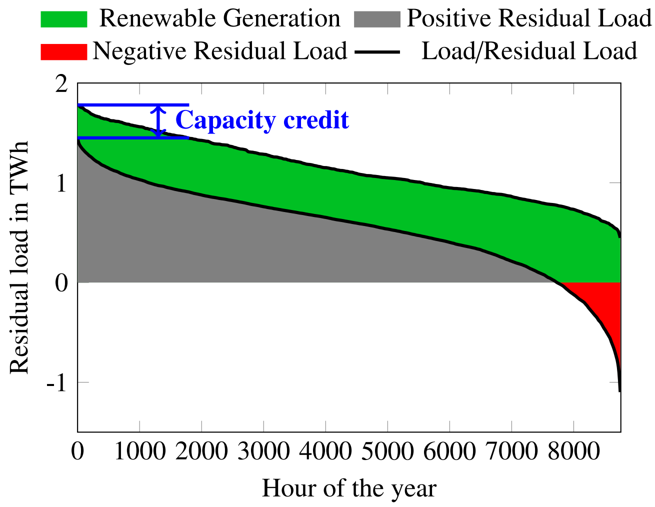

Figure 5: Measures to evaluate the VRE mix. The capacity credit is the difference between the maximum value of load and the residual load. The sum of negative and positive residual load is depicted as green or red area respectively.

our scenarios with different combinations of α and β is illustrated in Fig. 6 on the left. The figure depicts the huge amounts of renewable energies that are required to achieve a significant capacity credit. A system where 100% of the demand is generated by wind power as proposed by [11] will have a capacity credit of around 250 GW, which is only 15% of the peak load of 1,784.9 GW in 2030. The same capacity credit could be reached in a system with only 50% of renewable generation when considering a mix of wind and PV. The figure clearly shows that the mix of wind/PV matters when high capacity credits should be achieved. The following conclusions can be drawn:

- For low values of VRE penetration (lower α), a higher percentage of PV (higher β) is beneficial for the system. This can be explained by the correlation of the PV generation with the peak load during noon that can be reduced.

- The situation changes with higher percentages of VRE in the system. The remaining peak will not be during noon anymore but in the early evening where PV power is low and demand rises. The optimal portion of PV decreases to 20% for systems with very large amounts of VRE.

In order to point out the described effect further, Fig. 6 shows the relative capacity credit on the right. It is the portion of installed capacity that contributes to a reduction of the required conventional capacity. With low shares of up to 10% of the electricity generation, installed PV generation has a relative capacity credit of up to 15%. This means that 1 GW installation of PV can replace 150 MW of conventional peak generation. For VRE percentages of more then 20% in the system, this value is reduced drastically to around 5%. Installations of wind power show lower capacity credit of 5% at low installations down to 3% at a fully wind-powered system.

3.2. Sum over Negative and Positive Residual Loads

As stated in the introduction, an increasing portion of VRE will lead to overproduction in particular hours. This excess electricity has either to be stored, balanced by DSM, or curtailed. In any case, it causes additional system costs that should be avoided. An indicator for occurring overproduction is the sum of negative residual loads as depicted in Fig. 7. In a real world power system, overproduction will be higher as a certain portion of conventional power plants has to be online to provide ancillary services [30],[31]. Again, we can see a clear impact of the mix on the system requirements:

- Renewable energy of up to 20% of the electricity consumption can be fully integrated without storage.

- The maximal percentage of VRE that can be fully integrated can be found at a VRE share of 25% with a β of 0.4.

- For higher percentages of VRE, the excess electricity is lowest for a β of around 20-25%.

In this analysis, we are also interested in the amount of energy that still has to be provided by conventional sources which can be expressed as the sum over positive residual loads. This sum is related to the negative residual loads that remain, however, additional insights to the problem can be derived from Fig. 7 on the right:

- Again, we can see that 20% of the electricity supply can be supplied by wind and solar without any system problems.

- Achieving higher shares becomes more and more difficult, even a generation of 100% of the annual consumption by wind and solar will only supply 50-75% of the required electricity when analyzed on an hourly basis.

- Again, a β of around 20-25% turns out to be the best for systems with high penetration of VRE.

3.3. Storage Requirements

Another important criteria that we are analyzing is the required storage capacity that would allow a full integration of all renewable sources. The storage capacity has to be sufficient to store all occurring excess generation from wind and PV. This energy can then be released whenever generation is less than demand. The basic idea behind our approach was described in [16], where storage requirements for systems with more than 100% generation from VRE were analyzed.

In the following, we want to describe how we modified this approach in order to analyze scenarios with less than 100% of VRE generation. For the sake of simplicity and for focusing on our main aspects, we assume lossless storage. The results for the required storage capacities can be scaled by a loss factor, however, the structural results will not change. We measure the required reservoir energy content and not the pump/turbine power. The pumps and turbines have to be expanded as well but the reservoir is the more restrictive component when very large

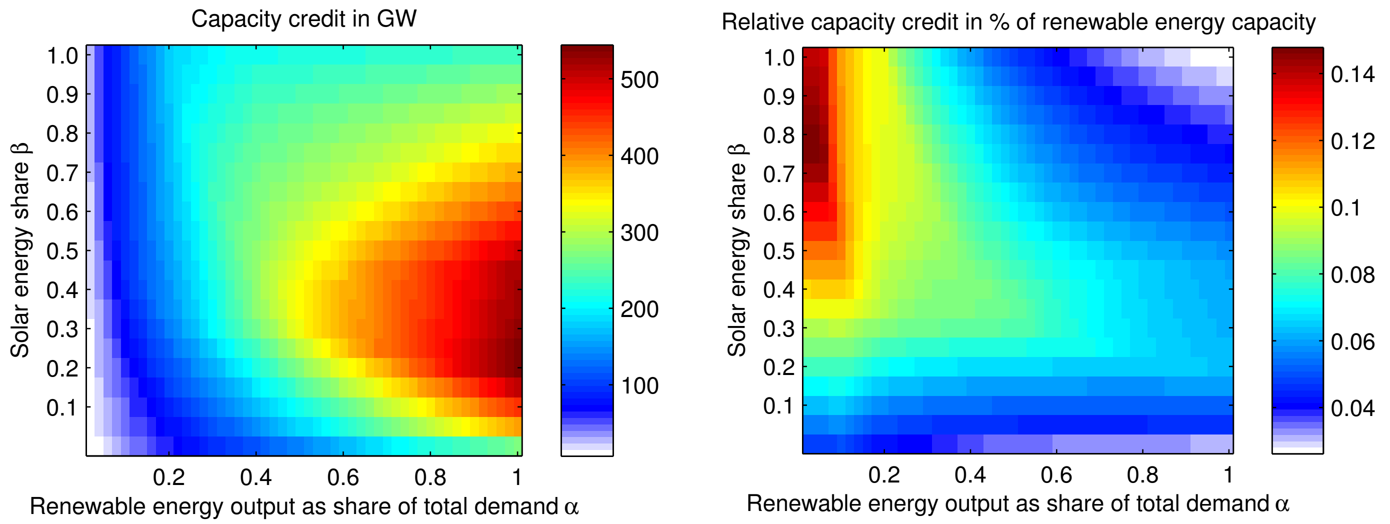

Figure 6: Capacity credit in absolute terms (left) and relative capacity credit (right).

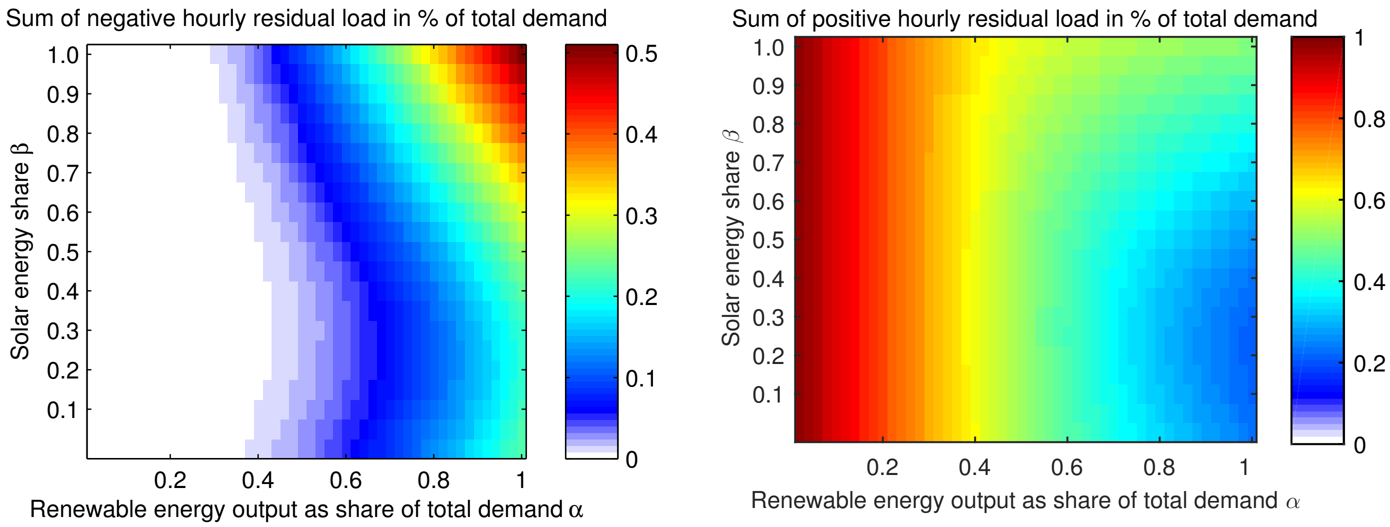

Figure 7: Sum over negative hourly residual load on the left and sum over positive residual load on the right.

amounts of energy have to be stored. The storage level $H(t)$ in every time step can be formulated with the residual load $RL(t)$ in every hour of the year:

$$H(t) = H(t-1) + RL(t). \quad (4)$$

In [16], the average RL is below zero as scenarios with more than 100% VRE are analyzed. This leads to a storage level $H(t)$ that shows an upward trend. In our case, it is the other way round, as average RL is positive and thus, storage level shows a decreasing trend (see Fig. 8 top for the residual load and Fig. 8 for the reservoir level). We therefore modify the approach of [16] and formulate the required storage reservoir capacity by:

$$E_H = \max_t(\max_{t'>t}(H(t') - H(t))). \quad (5)$$

A storage of the reservoir capacity E_H would allow to store the entire excess energy for each scenario. As it might not be efficient from an economic point of view to completely integrate all energy from VRE (e.g. see [32], [33], [34]), we allow 5% of generation from wind or PV to be curtailed (or maybe used for other purposes, e.g. electric heating or electric vehicles). This alternative assumption changes the results again as can be seen in Fig. 9 where both scenarios are compared: a complete integration on the left and 5% curtailment on the right. The figure shows that significantly more generation from wind and solar can be absorbed by the system whenever curtailment is allowed. In our opinion, this use-case seems the more realistic one for a future Chinese electricity system. If the entire production should be included in the system, storage will be required beginning with a VRE generation of more than 20%. However, when allowing curtailment of up to 5% of generation, up to 40% of renewable generation can be integrated without expensive storage technology. Requirements are lower with mainly wind powered systems for low overall generation (small α), whereas with higher α, more PV in the mix reduces storage

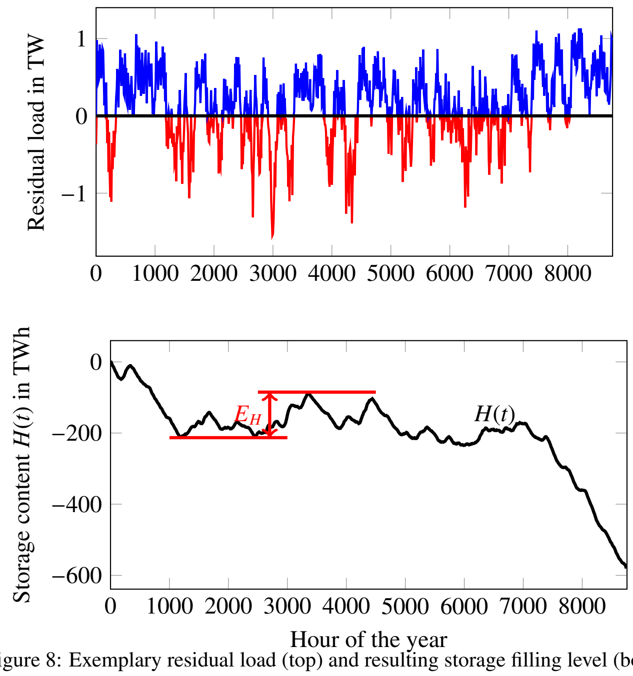

Figure 8: Exemplary residual load (top) and resulting storage filling level (bottom)

requirements. The reason for that is the higher seasonality in wind generation which requires storage for longer periods than daily up and downs.

The requirements for storage increase moderately at the beginning but tend to grow exponentially at around 70-80% of VRE in the system. Fig. 10 illustrates this effect: regardless of the chosen β, the storage requirement increases to values that seem not viable (more then 500 TWh of storage) as soon as 70-80% generation from wind and solar is reached. The log scale figure on the right allows analyzing the impact of the chosen β on lower levels of α. The figure shows, that a more even mix (β=0.5) allows for the integration of more renewables without any storage. The increase of storage requirements up to a level of 10 TWh is much lower with a generation mix than with either only wind or only PV. We thus consider these results as another advantage of combining the sources - wind and PV - to a hybrid renewable system. The resulting storage requirements of up to several hundreds to thousands of TWh is far away from being realized and we assume that won't change in the next decades. Current storage capacity is 16 GW [35], which gives an energy content of maybe 1 TWh when assuming a reservoir of 50 hours (European storages have a reservoir in the range of 30 hours according to [36]). We assume that in those scenarios of renewable integration other technologies would help in the balancing challenge which could be a large scale DSM with sector coupling with heating and transportation as described e.g. in [23] for China.

4. The Search for the Optimal Mix

Having analyzed the effects of wind and solar generation on the residual system, we want to approach the question of the optimal mix between wind and PV generation β_{opt} in the future Chinese power system. We illustrate the mix that maximizes the system value according to our measures for all scenarios of VREs up to 100% of generation in Fig. 11.

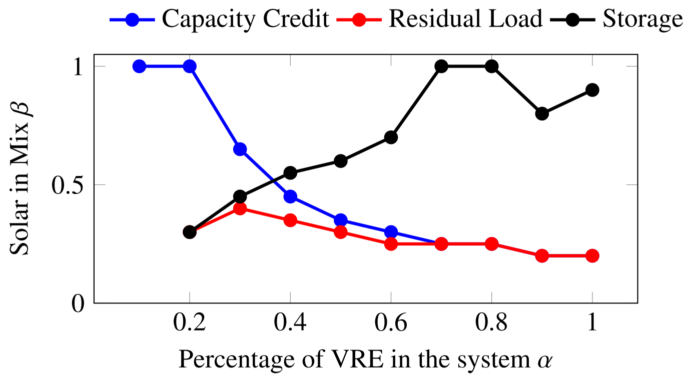

Figure 11: Optimal percentage of solar power in the VRE mix according to the three criteria described in this article.

The figure shows that the optimal mix between wind and solar generation depends on their combined share α that is installed. For low values of α up to 40%, higher shares of PV are beneficial as they reduce the peak load around noon and thus contribute to a higher capacity credit. Residual load is almost always positive and therefore storage is not required up to 20% of electricity provided by wind and solar generation. It is therefore recommended to install PV, especially in the first phase of a transition towards more renewable energy. In the range of α being between 20% and 50%, we see a very balanced mix to be the best solution for all our measures. The optimal β concerning the capacity credit is falling rapidly from 100% to 50% and below. Peak load during noon is already reduced and further capacity credit cannot be "earned" during that time of the day; peak residual load has shifted to late afternoon hours. With even more VRE in the system (α > 50%), defining the optimal mix becomes complex and uncertain: Concerning storage requirements, the best would be an almost fully solar-powered system. This can be explained by the stronger seasonal effects of wind power in China whereas electricity from PV mainly has to be stored from day to night. This is in contrast to what researchers found for Europe and might also need further work. In our research, only the reservoir energy content was considered; the required power capacity might show a contradictionary result. Still, it is clear, that solar generation is less seasonal in China than in central Europe as it is located closer to the equator and especially cloudy during summertime. Concerning the capacity credit and the overall negative residual load, the optimal share of PV is only 20%. In order to give a recommendation for system planners, the question about the excess electricity has to be answered: If everything is to be stored with daily storage, a PV based system could have advantages. In contrast, if it turns out that daily storage is too expensive and there are others solutions like power to heat [23] or power to gas, a mainly wind powered system with about 20-30% of PV generation is the best solution for a system with very high shares of VRE in China.

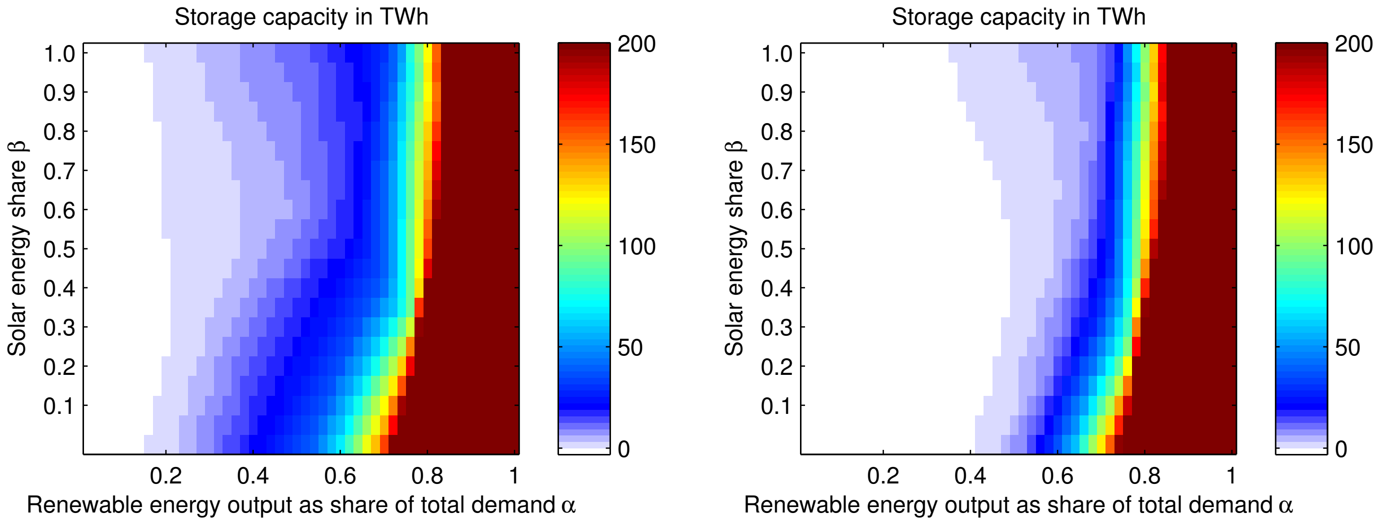

Figure 9: Storage requirements for different α and β. The scenarios on the left assume a complete integration of all generation whereas on the right a 5% curtailment is allowed.

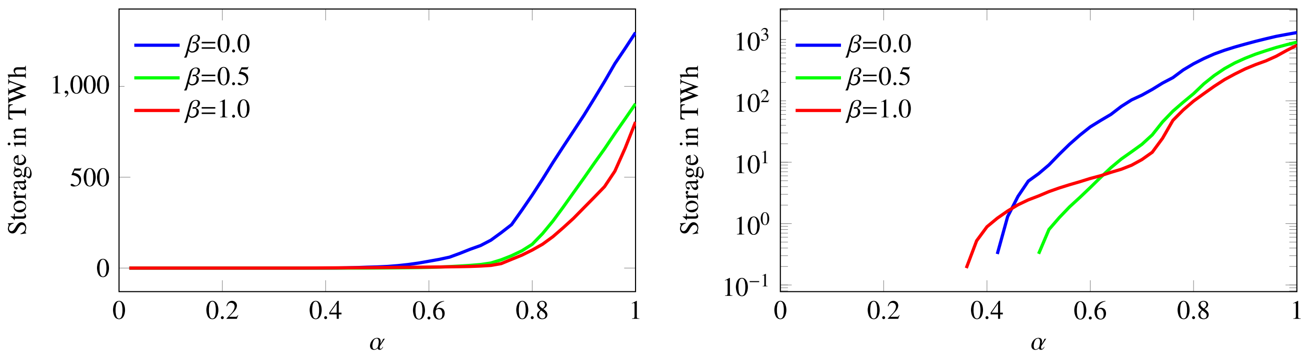

Figure 10: Storage requirements at different β for the case where 5% curtailment is allowed. Normal scale is illustrated on the left and a log-scale is used on the right to illustrate the low values in more detail.

5. Conclusion: Recommendations for System Planning and Renewable Energy Policy in China

Our results confirm the hypothesis that was proposed by researchers from the Harvard China project: China could be entirely powered by renewable energy sources like wind and solar. We saw that, indeed, it is possible to fully power China by generation from wind turbines calculated on a per year base. However, when considering the hourly timescale, it turns out to be more difficult. Even 100% generation of the annual electricity consumption by wind turbines will only result in a capacity credit of approximately 15%. There will be a huge portion of generation that will be produced in excess of current consumption and thus has to either be stored, curtailed, or used for other purposes. This situation can be significantly improved by additionally including a limited amount of PV for electricity generation. Thereby, the capacity credit can be increased dramatically. For a low combined percentage of wind and PV, the optimal mix includes up to 80% of PV. For a higher combined generation, these values are reduced down to 20% of PV in a fully renewable-powered China. In all considered scenarios, storage requirements increases exponentially to unrealistically high values as soon as 70% penetration of wind/PV are reached. To avoid this storage problem, alternatives like a sector coupling with either heating or transportation can be considered.

To sum up, our research showed that even with a generation that equals the demand on a per year base and an optimized mix of VRE, conventional power plants or large amounts of storage will be required to ensure a reliable power supply on an hour-by-hour basis. This shows the problem of renewable integration: conventional power generation or storage or both will be prevalent even in a system where generation of VRE equals demand on an annual basis. As a consequence of our analysis, we suggest planners pursue a system with a wind/PV mix of around 70/30% in order to have the lowest integration costs. We also suggest setting a goal of a maximum of 70% generation being provided by wind and PV as long as the storage problem remains unsolved.

The analysis in this article forms the basis for further research. The cost-optimal placement of generation and storage should be a focus of further research and discussion. Furthermore, large amounts of transmission grids will have to be installed, requiring research on optimal transmission expansion planning. All this research will help the planners to design a system with high shares of variable renewable sources at the lowest costs. Achieving low-cost solutions for VRE integration will be crucial for solving the current Chinese energy and environmental problems while keeping the economy on its high-growth path.

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Appendix A. Appendix

Appendix A.1. Overview of the modeled regions

Table A.1: Overview of demand, potentials, and full load hours in the modeled regions

Region	Demand [TWh]	Pot PV [GW]	FLH PV [h/a]	Pot Wind [GW]	FLH Wind [h/a]
Anhui	260	195	1035	56	852
Beijing	175	49	1156	9	1041
Chongqing	152	44	967	21	463
Fujian	322	214	1063	52	1998
Gansu	196	7360	1126	1318	1016
Guangdong	935	566	1095	116	1072
Guangxi	237	1613	1145	395	937
Guizhou	201	938	1089	270	783
Hainan	39	354	1038	55	1594
Hebei	635	876	1155	160	1432
Heilongjiang	171	3257	1002	439	1308
Henan	565	360	1077	86	837
Hubei	308	892	990	247	624
Hunan	275	684	1016	201	780
Jiangsu	910	69	1063	9	1365
Jiangxi	178	825	1035	168	649
Jilin	134	1098	1056	146	1491
Liaoning	396	913	1180	144	1606
Nei Mongol	396	8655	1173	2123	1628
Ningxia Hui	154	1214	1152	191	1009
Qinghai	119	6029	1098	1627	1360
Shaanxi	209	1700	1068	328	879
Shandong	773	373	1125	50	1457
Shanghai	285	0	111	0	2057
Shanxi	351	812	1122	194	1129
Sichuan	372	1233	1085	786	842
Tianjin	148	26	1160	3	1213
Xinjiang Uygur	178	19537	1158	5543	1063
Xizang	5	13128	1211	3453	1628
Yunnan	256	1058	1265	447	600
Zhejiang	663	49	1061	14	1401

Appendix A.2. Resulting Capacities

In order to give an idea of the installed capacities in the considered scenarios, Table A.2 presents excerpts of the data.

Table A.2: Overview of installed capacities in some major scenarios

α (-)	β (-)	Wind (GW)	PV (GW)
0.2	0.0	1488	0
0.2	0.2	1183	364
0.2	0.5	729	908
0.2	0.7	435	1270
0.5	0.0	4071	0
0.5	0.2	3184	908
0.5	0.5	1896	2267
0.5	0.7	1107	3175
0.7	0.0	6059	0
0.7	0.2	4760	1270
0.7	0.5	2830	3175
0.7	0.7	1616	4446
1.0	0	8422	0
1.0	0.2	6756	1814
1.0	0.5	4071	4536
1.0	0.7	2312	6348