Energy Storage Requirements and Land Footprint for 100% WWS in Shandong Province

A Case Study of State Grid Shandong Electric Power Company

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Abstract. The global transition to wind, water, and solar (WWS) energy is crucial for addressing the climate crisis, a shift that is equally vital for China. Shandong Province, a major industrial hub, is poised to play a critical role in this energy transition. This paper uses the IEA 2022 data to study the energy storage needs and land footprint required for a 100% WWS system in Shandong: Approximately half of the energy would be derived from solar power, around 40% from wind, with the remainder coming from hydro, geothermal, and other sources. Solar power requires the largest land area, followed by wind power; thus, energy storage is key to balancing their intermittency. This study quantifies the requirements for Shandong's renewable energy shift and highlights the necessity of grid upgrades and the pivotal role of the State Grid Shandong Electric Power Company. The findings provide valuable insights for decision-makers and energy companies regarding optimal resource allocation and strategies for supporting China's carbon reduction goals.

Keywords: Energy Storage; Renewable Energy; Shandong Province; Wind Energy; Solar Energy

1 Introduction

1.1 Background and Significance

The global energy transition is essential to mitigating climate change, reducing air pollution, and enhancing energy security. As the world's largest emitter of CO_2, China's transition to renewable energy technologies, particularly WWS, is essential for achieving carbon neutrality. The most industrialized region in China, Shandong, is right in the middle of this change, facing the dual challenge of maintaining energy supply security while reducing carbon emissions. The transition to a 100% wind, water, and solar (WWS) energy system in Shandong entails not only a reduction in dependence on coal and fossil fuels, but also establishes a significant demonstrative model for other prov-

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inces in China. This shift exemplifies a pathway toward deep decarbonization and sustainable energy transformation at the regional level. This research is significant because it provides data-driven insights into the energy storage and land use requirements essential for this transition, which can help policymakers and energy companies formulate effective strategies.

1.2 Research Status

Globally, the research on renewable energy system mainly focuses on technology application and economic benefit of using wind, solar, and hydro generation for integration into existing electrical grids. Countries such as Germany, Denmark, and Spain have already achieved considerable development in renewable energy application. Most studies, however, focus on national transitions, with little attention given to the provincial level, especially in China. The country has set ambitious goals for its renewable energy use: by 2025, the share of China's energy derived from non-fossil sources should reach 20%. However, it is evident that energy storage, land for solar panels and wind farms, and grid integration pose serious technical and infrastructural obstacles. At a provincial level, there's already some integration of renewable energy taking place in Shandong but the challenges of land use optimization and furthering energy storage tech still exist.

1.3 Research Topic

This study investigates the energy storage requirements and land footprint for a 100% WWS energy system in Shandong Province. It aims to:(1) quantify the storage capacity needed to address the intermittency of solar and wind power; (2) evaluate the land area required for renewable energy infrastructure; and (3) analyze the critical role of the State Grid Shandong Electric Power Company in facilitating this transition. Furthermore, it provides recommendations for overcoming technological, financial, and spatial barriers, with a focus on energy storage alternatives, land-use strategies, and necessary investments.

2 Energy Transition in Shandong Presently

2.1 Shandong's Energy Use Profile

Shandong Province is one of China's largest energy-consuming regions, with its power demand driven by diverse industries. At present, Shandong's energy consumption is mainly from traditional fossil fuels, especially coal. According to IEA (2022) data, coal remains the primary energy source, especially in the industrial and residential sectors. Oil and natural gas also play significant roles, particularly in transportation and heating. Electricity consumption has been increasing steadily, with the industrial sector being the largest consumer, followed by the residential and commercial sectors [1].

Even though they are trying to use different types of energy, renewable energy sources like WWS are still not much of the total energy used in Shandong [2]. Although renewable power capacity has expanded significantly in Shandong, the province's energy mix remains heavily dependent on fossil fuels, particularly coal. Getting off coal is important for cutting carbon emissions and staying sustainable in the long term.

2.2 Renewable Energy in Shandong

The deployment of renewable energy infrastructure by Shandong has been significant, especially with wind and solar energy. The province enjoys advantageous geographical conditions for both wind and solar energy, which means considerable wind farms and solar power plants can be found there. Wind energy, in particular, has seen much development because the province is open and the winds are strong. And solar is growing as well: utility scale, rooftop solar, more of all of those.

Though it is so, renewable energy only accounts for a very little part of the total energy consumption in Shandong. Current estimates place renewable energy sources as contributing around 15–20% of the province's energy needs with the rest still coming from fossil fuels. which indicates that more efforts and investment are needed to have more renewable energy in the province [3].

Wind and solar, which are renewable energy sources, are intermittent so there are some issues with adding them to the existing grid. This intermittency necessitates the development of effective energy storage solutions to ensure a reliable and stable power supply. In addition to that, Shandong's energy grid infrastructure needs upgrading so it can cope with the variability of renewable energy and work better as part of the larger power system.

2.3 Existing Energy Storage Infrastructure and Land Utilization

Energy storage facilitates the integration of renewable energy into the power system. However, Shandong's current energy storage infrastructure is inadequate to meet its needs. Although there is some pumped hydro storage ability in the province, the total storage capacity is not sufficient to deal with the fluctuations in renewable energy production. More people's interest about battery storage technology such as lithium batteries is positive but is faced with the issues of cost and scalability.

When talking about land use, in order to install renewable energy systems in Shandong, it is necessary to have extensive land areas, particularly with respect to solar and wind energy. The province is large in area, even more so in rural and remote regions. Conflicts over the use of the land arise when projects for renewable energy compete with agricultural land, cities, and zones for the preservation of nature. With accelerating urbanization development in Shandong, it is becoming more limited to find land available in urban areas for renewable energy projects.

For such problems, it requires good land use. It will be necessary to balance requirements for expanding renewable energy installations alongside agriculture and urban development. Policies that make approval easier for renewable energy projects and pay landowners to reserve land for renewable energy would help.

3 Supply-Demand Analysis of Energy Storage and Land Use for Renewable Resources

3.1 100% WWS System Energy Storage Needs

Energy Storage Capacity Estimation. Accurate estimation of energy storage capacity is crucial for ensuring a steady and reliable power flow in Shandong's 100% WWS energy system. The fact that renewable energy sources such as wind and solar energy are intermittent requires the need for a storage system that is able to store the excess electricity generated at the time the production is higher, and release the stored energy during periods of lower production. To determine the required energy storage, it is necessary to consider the proportion of renewables used in Shandong compared to those across China, as well as fluctuations in energy production.

Energy storage is required to address periods when renewable generation cannot meet demand, such as during cloudy conditions or periods of low wind. The required storage capacity must be calculated using models of Shandong's electricity consumption so that the system can meet the demand when there is a lack of renewable energy sources. The energy storage capacity will be decided by the maximum energy that will be used, how much that usage will change over time, and how much renewable energy is made.

Technologies for Energy Storage. Several energy storage technologies, tailored to local conditions, can support the transition to a 100% WWS system in Shandong. The most viable technologies must be scalable, cost-effective, and capable of providing both short- and long-duration energy storage. Among the most prominent technologies, lithium-ion batteries are also the ones currently most used for storage. They exhibit high energy density and rapid response capabilities, fit in short-time energy storage tasks where demand sways by the day. However, while excellent for short-duration storage, the spatial footprint and high cost of deploying large-scale lithium-ion battery arrays make them less economical for long-duration storage applications.

Pumped hydro storage (PHS) is another common technology that is suitable for big size, long-term energy storage. It makes use of extra energy when demand is low by pumping water to a higher place. when demand goes up the reserved water is let out for creating power (Pumped Hydro Storage) PHS has a high efficiency rate and can be an efficient renewable energy balancing tool. However, it has limitations because of geography and environment - finding right places to make big lakes for water, and the construction of large reservoirs can have significant environmental impacts. Compressed Air Energy Storage (CAES) compresses air and stores it in underground caverns. When there is great electricity consumption, the air pressure is let out and turned into energy. CAES has great potential for large-scale storage and can make a difference in Shandong' energy transition. However, it is challenging to find a place to build cavern underground everywhere, so it's hard to use it [4].

Each of these technologies exhibits distinct strengths and limitations. The adoption of energy storage systems in Shandong will depend on multiple factors, including cost,

efficiency, and compatibility with the province's unique geographical conditions. A comprehensive evaluation of these factors will enable the identification of the most suitable storage solutions to integrate with Shandong's renewable energy infrastructure.

3.2 Renewable Energy Infrastructure Land Footprint

Solar and Wind Farms Land Area. In order to power Shandong with renewables, a large number of new solar and wind farms will be required. Solar energy requires large areas of land to install photovoltaic panels, which should be placed in regions with high solar radiation to ensure efficiency. Wind energy also requires vast open spaces for setting up wind turbines, which need a consistent wind speed.

The total land required in Shandong for solar and wind energy can be calculated based on energy demand and the efficiency of energy technologies, respectively. Solar farm: Based on solar farms, it is dependent on what capacity the panels used in the installation can produce, with regard to the energy that will be generated by each panel installed. Meanwhile, wind farms do need to leave space between the turbines to reduce the wind turbulence and optimize power generation, which makes them take up much more space.

An accurate estimation will be derived based on the total energy consumption of the province, the efficiency of renewable energy technologies, and the land area required for energy storage facilities and grid connections. Furthermore, land availability in Shandong, particularly in rural regions, will also significantly influence the feasibility of such deployment [5].

Spatial Possibilities & Land Clashes. Shandong possesses extensive rural regions with potential for renewable energy development; however, considerable land-use challenges persist. Competition for land is intensifying among renewable energy facilities, agricultural production, urban expansion, and environmental protection zones. Notably, many areas most suitable for solar and wind farms overlap with prime agricultural land, which may constrain the availability of territory for energy infrastructure. Moreover, rapid urbanization in Shandong is reducing the amount of undeveloped land available for large-scale renewable energy projects. High population densities in urban areas further limit opportunities for siting energy installations within cities. Environmental considerations—such as the preservation of biodiversity and ecological balance—also complicate land-use decisions for new energy facilities. Strategic land-use planning and zoning could help alleviate these tensions. Delineating specific zones for renewable energy development, while conserving land for other critical societal needs, requires a balanced and integrated approach to spatial planning that accommodates multiple competing demands.

4 Regional Comparative Analysis

Compared to other areas, Shandong presents unique conditions for renewable energy deployment. Inner Mongolia is an example where it has big pieces of land inland and a

lot of winds that would have a large onshore wind farm with limited land conflicts. However, its capacity factor for wind power, typically ranging from 20% to 30% (CWEA, 2023; NEA, 2022), is generally lower than that of coastal provinces. On the contrary, Shandong's coastal geography facilitates offshore wind development, which has capacity factors of 35-45% (IEA, 2022; CWEA, 2023) and thus increases output efficiency but at greater construction expense [6].

Jiangsu, another coastal province, also develops offshore wind. However, it faces land constraints because of its dense population and urbanization. Consequently, it relies more heavily on small-scale distributed solar projects on rooftops and industrial sites, (IEA, 2022). While Shandong shares a substantial coastline with its eastern neighbor Jiangsu, its larger total land area presents an additional advantage for deploying utility-scale solar farms.

These regional comparisons underscore that Shandong's energy transition strategy must leverage its maritime advantages, optimize terrestrial siting for renewables, and modernize its grid infrastructure. This comprehensive approach is essential to bridge the gap between the province's concentrated industrial energy demand and the distributed, variable nature of its solar and wind resources [7].

5 Shandong's Energy Transition SWOT Analysis

5.1 Strengths

Shandong possesses several strengths in transitioning to renewable energy. The province has superb geographic circumstances for creation of both wind and sun energy, wind blowing very strongly all around its coast sections and sunlight being pretty high through almost the complete place. Also, Shandong already has an established energy infrastructure, including a substantial amount of energy consumption as well as industrial potential, which is quite suitable for the inclusion of additional forms of energy.

Government support for the development of renewables is also an advantage. National policies like subsidies and incentives for renewable energy projects create a good environment for using renewable energy in Shandong. As for the province, it hosts many more and more renewable energy related research and developing projects, which makes itself to be the leading area of clean energy innovation.

5.2 Weaknesses

Although the advantages of Shandong are recognized, there are still some weaknesses in energy transformation. The province remains heavily dependent on coal and natural gas for power supply; it is not easy to decrease carbon emissions promptly. There is a lack of advanced energy storage system, it is necessary for balancing the renewable energy generation. The current energy grid infrastructure was not created with the aim to have large amounts of renewable energy. It will require large upgrades for the grid to be stable [8].

Land use restrictions are also a large issue. Much of the best land for renewable energy projects is already used for agriculture or cities, so there's little room for big renewable facilities [9].

5.3 Opportunities

Renewable Energy Transition. Shandong has opportunities for its renewable energy transition. Shandong has the chance to turn into a front-runner when it comes to renewable energy development because the increasing need for clean energy comes along. The province can take advantage of its massive renewable energy resources to create jobs, innovation and economic growth in the clean energy industry [10].

Moreover, Shandong is in line with the national energy transition goals, it can also work together with the central government and other provinces. Expanding its renewable energy capacity will make Shandong eligible for national incentives and facilitate the development of its energy infrastructure.

5.4 Threats

Shandong will have difficulties in changing to a system of 100% WWS due to certain risks. The high capital costs associated with renewable energy infrastructure and energy storage technologies could delay the transition. Moreover, resistance from the traditional energy sectors - especially coal and natural gas industries would impede the transition to renewable energy.

Another big problem is that renewables come and go. The difficulty with providing a dependable and stable power source via wind and solar energy still exists, and without adequate power storage, that switch will be very complicated.

The insights from this SWOT analysis highlight the critical factors influencing Shandong's renewable energy transition, which are essential for formulating effective strategies.

6 Strategies for Overcoming Barriers and Helping out in Energy Transition

6.1 Strategies for Addressing Energy Storage Challenges

Enhancing Energy Storage Capacity. To increase Shandong's reliance on the WWS system, its energy storage capacity must be increased. One way to achieve this is by using large batteries, such as lithium-ion batteries, which have high energy density and fast response times. Although lithium-ion batteries are currently expensive, mass production could drive down costs, making them more viable for large-scale deployment. Another important technology, PHS, is already used for longer energy storage time. In order for energy storage to happen, the PHS system should be popularized in places with the right geography. Additionally, a decentralized energy storage approach should be encouraged, promoting the widespread adoption of small-scale storage systems

among households, businesses, and industries. This distributed approach would reduce the strain on large centralized storage facilities and enhance grid resilience.

Policy Support for Storage Technologies. Government policies are crucial to fostering the development of energy storage technologies in Shandong. Financial incentives, including subsidies, tax exemptions, and other fiscal measures, should be introduced to stimulate investments in energy storage from both public and private entities. Furthermore, significantly increasing funding for research and development is essential to advance storage systems that are not only more cost-effective but also better tailored to Shandong's specific energy conditions and requirements. According to the Shandong Province 14th Five-Year Energy Development Plan (Shandong Provincial Government, 2022), the province plans to increase the proportion of non-fossil energy consumption to around 15% by 2025, with renewable energy installations reaching almost 9,000 MW, new-type storage capacity above 600 MW. These targets do constitute steps forward; however, they are still nowhere near the standards set for the 100% WWS system – which would require an almost total dependence on renewable energy sources and greatly increased storage capacities in order to compensate for the irregularity of power generation. This policy gap points out the way forward in future improvements: boost deployment of storage, align policy rewards with the long run vision WWS aims at, improve institutional support so as to drive Shandong towards its transition faster [11].

6.2 Suggestions for Promoting Renewable Energy Development

Incentivizing Renewable Energy Projects. Shandong should speed up the deployment of renewable energy given the government's willingness to promote renewable investments through attractive policies. Tax credits and feed-in tariffs can draw both national and international investors with money rewards to create wind, sun, and water power projects. And also, regulatory help like simplifying permits and giving extra stuff to those who make renewable energy can greatly lower the things needed for projects to happen. Shandong gives out money rewards and good rules to make the renewable energy business grow big.

Promoting Grid Integration and Upgrades. Successfully integrating renewable energy into Shandong's grid is going to need pretty major improvements to how things work right now. Investments in smart grid technology would allow for better management of renewable energy resources by balancing supply and demand in real time. These technologies can enhance grid efficiency, flexibility, and reliability. More loads need to be taken up by grids as well because the grid capacity must be increased for renewable energy. These grid upgrades will see Shandong's renewable energy systems hooked up to the bigger electricity network so it delivers stable and reliable power [12].

6.3 State Grid Shandong Electric Power Company Recommendations

Strategic Role in Energy Transition. State Grid Shandong Electric Power Company plays an important role in leading the transition to a 100% WWS system in Shandong province It must give priority to the integration of renewable energy into its existing infrastructure, concentrating on increasing and upgrading the grid so as to fit more renewable power generation. Also, it should invest in advanced energy storages for the solar and wind power which is very intermittent. As long as the State Grid Shandong Electric Power Company plays an active part in the infrastructure upgrading and the popularization of the use of renewable energy, the province will be heading towards the energy transition target [13].

Cooperation with local government and relevant parties. State Grid Shandong Electric Power Co., Ltd., local governments and others must work together effectively if renewable energy projects are to be deployed successfully. Collaboration between developers, government agencies, and local communities is key to obtaining permits efficiently, resolving land use issues, and maintaining community support. State Grid Shandong Electric Power Company should work with local governments to find suitable land for renewable energy projects and transition accordingly. Also interacting with other people like the environmental groups and local people would help get support from the general public for using renewable energy, and reduce people being against the plan.

Integration with Power Spot Market and Storage Value Recovery. State Grid Shandong Electric Power Company should improve the linkage between the integration of renewal energy and the Shandong power spot market. A spot market is operational: electricity prices represent the current supply and demand for electricity, and storage systems can recover value by exploiting the difference between peak and off-peak prices on the market, and providing ancillary services through the spot market. By aligning storage deployment with market mechanisms, the company can reduce wind and solar curtailment, stabilize the grid, and ensure storage projects are financially rewarded. This mechanism is essential to allow for the economic viability of large-scale storage and allow Shandong to achieve 100% WWS as soon as possible.

7 Conclusion

This study has investigated the energy storage requirements, land footprint, and feasibility of transitioning to a 100% WWS energy system in Shandong. The key findings indicate Shandong boasts abundant renewable energy resources, particularly in wind and solar power. However, the integration of these variable sources into the power grid necessitates substantial investment in energy storage technologies and significant land allocation. Effective storage systems are essential to balance the intermittency of renewable generation, while the development of solar and wind farms must contend with competing land-use demands. Furthermore, large-scale renewable energy integration

will require considerable upgrades to existing grid infrastructure and overcoming current technical limitations to ensure reliability and stability.

Looking ahead, there's a strong long-term opportunity for renewables in Shandong - plenty of possibilities to get much more wind, solar and storage up and running. However, this transition must overcome challenges such as land-use conflicts, high capital costs, and the technical complexities of integrating large-scale storage and renewable generation into the grid. Shandong plays a significant role in China's overall transition to renewable energy, because Shandong can be an example for others. The province will need to strategically invest in renewable energy, modernize grids and energy storage in order for it to have sustainable energy sources.

This study is highly relevant for energy companies, policymakers, and other stakeholders. It gives a clear path for moving on a 100%WWS system, which can give helpful knowledge about the special demands and hard jobs Shandong will run into. Also, the results stress the necessity of provincial strategies matching at the same level of national goals, the Shandong energy transformation contributing to the bigger target of China's carbon neutrality.

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