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A Comparison of Solar and Wind Energy Development Between Western China and the Western US

Haoge Xu
University of Pennsylvania

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Abstract

China and the US are pursuing carbon neutrality targets as the world's largest emitters. Powered by renewable energy, green electricity is a crucial step to help both countries to realize their carbon neutrality goal. Having similar natural situations and abundant solar and wind resources, both countries' western regions shared significant similarities in the weight of land size, population, and social economy to the nation, which makes both western regions comparable. However, both countries are currently at different developing paces in developing solar and wind energy, which requires an unbiased method to conduct this assessment. This study designed a renewable energy assessment framework by defining vital influential factors and their sub- factors first, then aggregating all normalized values of selected factors to conduct a final performance score for each province and state in both western regions. Additionally, a ranking can be given within each region based on the final normalized score. Overall, the results show that although the two western regions are in different development stages, both share similarities in their solar and wind performance except the performance on social policy, as the western US has more types of solar, and consumers can choose incentives. At the provincial and state level, the top three performers in western China and the western US are Inner Mongolia, Qinghai, Ningxia, Colorado, Arizona, and Wyoming, respectively. Based on the performance result, recommended policy implications are given to both western regions for future usage. This framework can be applied to other renewable energy development assessments after successfully defining the key factors and their sub-factors.

Keywords

Western China; the western United States; solar energy; wind energy; renewable energy development

Disciplines

Environmental Sciences | Physical Sciences and Mathematics

A COMPARISON OF SOLAR AND WIND ENERGY DEVELOPMENT BETWEEN WESTERN CHINA AND THE WESTERN US

Haoge Xu

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Jinping Tian, PhD

Yvette Bordeaux, PhD

ABSTRACT

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Jinping Tian Ph. D.

China and the US are pursuing carbon neutrality targets as the world's largest emitters. Powered by renewable energy, green electricity is a crucial step to help both countries to realize their carbon neutrality goal. Having similar natural situations and abundant solar and wind resources, both countries' western regions shared significant similarities in the weight of land size, population, and social economy to the nation, which makes both western regions comparable. However, both countries are currently at different developing paces in developing solar and wind energy, which requires an unbiased method to conduct this assessment. This study designed a renewable energy assessment framework by defining vital influential factors and their sub-factors first, then aggregating all normalized values of selected factors to conduct a final performance score for each province and state in both western regions. Additionally, a ranking can be given within each region based on the final normalized score. Overall, the results show that although the two western regions are in different development stages, both share similarities in their solar and wind performance except the performance on social policy, as the western US has more types of solar, and consumers can choose incentives. At the provincial and state level, the top three performers in western China and the western US are Inner Mongolia, Qinghai, Ningxia, Colorado, Arizona, and Wyoming, respectively. Based on the performance result, recommended policy implications are given to both western regions for future usage. This framework can be applied to other renewable energy development assessments after successfully defining the key factors and their sub-factors.

Keywords: Western China; the western United States; solar energy; wind energy; renewable energy development

ABBREVIATIONS

BIPV	Building-integrated photovoltaics
China	People’s Republic of China
CO2	Carbon dioxide
EIA	The U.S. Energy Information Administration
GHG	Greenhouse gas
GDP	Gross domestic product
GDP per capita	Gross domestic product per capita
RMB	Chinese yuan
PV	Photovoltaics
NEA	The National Education Association
US	United States
USD	United States dollar

VARIABLES

C annual total consumption
D electricity usage deficit
G total annual generation
N_{score} normalized aggregate solar & wind development performance score for a province or state
W_x weight of factors
N_x weight of the normalized value for different factors
W_e weight of the normalized economic score
W_s weight of the normalized social policy score
W_i weight of normalized installation score
W_g weight of normalized generation score
W_{gc} weight of normalized grid connection score
W_t weight of normalized transmission score
W_c weight of normalized consumption score
V_{gdp} weight of GDP per capita,
V_{income} weight of disposable income per capita
V_{Ctax} weight of corporate tax credit
V_{PStax} weight of personal tax credit
V_{PPtax} weight of property tax credit
V_{Rebate} weight of rebate
$V_{Net\ Metering}$ weight of net metering
$V_{5\text{-}year\%Ins\text{-}wind}$ weight of 2015-2020 average new installation ratio for wind
$V_{5\text{-}year\%Ins\text{-}solar}$ weight of 2015-2020 average new installation ratio for solar
V_{cwind} weight of cumulative installed capacity wind
V_{csolar} weight of cumulative installed capacity solar
$V_{\%\_Gwind}$ weight of 2015-2020 average wind curtailment rate
$V_{\%\_Gsolar}$ weight of 2020 Percent of electricity generated by solar
$V_{curtail\text{-}wind}$ weight of 2015-2020 average wind curtailment rate
$V_{curtail\text{-}solar}$ weight of 2015-2020 average solar curtailment rate
V_{trans_loss} weight of transmission loss
$V_{trans\_Reliability}$ weight of transmission reliability
V_{export_import} weight of export/import statu
$V_{consumption}$ weight of 2020 electricity deficit index
N_e normalized economic score
N_s normalized social policy score
N_i normalized installation score
N_g normalized generation score
N_{gc} normalized grid connection score

N_t	normalized transmission score
N_c	normalized consumption score
N_{gdp}	normalized GDP per capita
N_{income}	normalized disposable income per capita
N_{Ctax}	normalized corporate tax credit
N_{PStax}	normalized personal tax credit
$\mathrm{N}_{\mathrm{PPtax}}$	normalized property tax credit
$\mathrm{N}_{\mathrm{Rebate}}$	normalized rebate
$N_{Net\ Metering}$	normalized net metering
$N_{5\text{-}year\%Ins\text{-}wind}$	normalized 2015-2020 average new installation ratio for wind
$N_{5\text{-}year\%Ins\text{-}solar}$	normalized 2015-2020 average new installation ratio for solar
N_{cwind}	normalized cumulative installed capacity wind
N_{csolar}	normalized cumulative installed capacity solar
$N_{\%\_Gwind}$	normalized 2020 Percent of electricity generated by wind
$N_{\%\_Gsolar}$	normalized 2020 Percent of electricity generated by solar
$N_{curtail\text{-}wind}$	normalized 2015-2020 average wind curtailment rate
$N_{curtail\text{-}solar}$	normalized 2015-2020 average solar curtailment rate
N_{trans_loss}	normalized transmission Loss
$N_{trans\_Reliability}$	normalized transmission reliability
N_{export_import}	normalized export/import status
$N_{consumption}$	normalized 2020 electricity deficit index

UNITS

km	Kilometre
km^2	Square kilometre
kWh	Kilowatt-hour
m	Metre
m^2	Square metre
m^3	Cubic metre
MWh	Megawatt-hour

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CHAPTER 1 INTRODUCTION

1.1 Carbon neutrality target in both countries

China overtook the United States as the world's biggest emitter of carbon dioxide in 2006, and both countries have shared the world's largest share of carbon emissions since then. In 2019, China's greenhouse gas emissions overtook the world's developed countries combined, about 14.1 billion metric tons, which occupied more than 27% of the world's total emissions. While the US, still the second largest emitter, shared 11% of the total world emission, about 5.7 billion metric tons (Rhodium Group, 2021; Regan & Dotto, 2021). The increasing global temperature caused by annually increasing GHG emissions forced global countries to cooperate. In 2015, including China and the US, 196 Parties adopted the Paris agreement to limit global warming to 2 Celsius degrees compared to pre-industrial levels (United Nations Climate Change, 2015). While in 2020, China pledged to peak greenhouse gas emissions by 2030 and reach net zero by 2060 (Climate Action, n.d.), comparably, as the US has reached carbon peaking in 2007 (Data Highlights, n.d.), in 2021, the US further committed that reducing greenhouse gas emissions by 50% to 52% by 2030 compared to 2005, and achieve carbon neutrality by 2050 (Hebei Department of Natural Resources, n.d.). Against this background, it is clear that China and the US have a long-term goal of pursuing carbon neutrality.

1.2 Current electricity generation & consumption of the US and China

Starting from 2011 (Electricity Production Data, n.d.), China generated the highest amount of electricity globally, followed by the United States. Figure 1 shows that in 2021 the US generated 4,116 billion kWh and consumed 3,897 billion kWh of electricity, while China generated 8,312.8 billion kWh and consumed 8,112.2 billion kWh of electricity. Among the generated electricity, the US used renewable energy to generate 827.3 billion kWh of electricity; on the other side, China generated 2,477.2 billion kWh of electricity by using renewable sources. Figure 2 shows the percentage breakdown by different sources. Interestingly, the percentage of electricity generated by fossil fuels, including coal, natural gas, petroleum, and other fossil fuels, in both country, was very close, about 65.16% in China and 59% in the US. For the dependency on fossil fuel usage, China relied on coal, and the US relied on natural gas due to their storage sufficiency. Similarly, including nuclear energy, which is a non-renewable energy but a clean source, US and China had

39.4% and 35% electricity, respectively. By only considering renewable energy, the weight of China seemed higher, about 30%, which benefited from its world's largest hydropower; however, the US only had 20.4% in 2021. Both countries' electricity generated by geothermal and biomass only occupied a little weight but solar, and wind combined occupied 12% simultaneously.

Unit: billion kilowatt-hours	2021 Total Electricity consumption	2021 Total Electricity Generation	2021 Electricity generated by renewable	Nuclear	Coal	Natural Gas	Petroleum & Other	Wind	Solar	Biomass	Geothermal	Hydrology
China	8,312.8	8,112.2	2,477.21	407.141	5,030.00	228	13	652.6	325.9	163.70	0.13	1,340.10
US	3897	4,116	827.316	778	899	1575	37	379.77	114.68	55.48	16.24	260.23

Figure 1 2021 US & China electricity generation & consumption details

Fig 1: The consumption and generation capacity of the US is about half of China's generation and consumption om 2021.

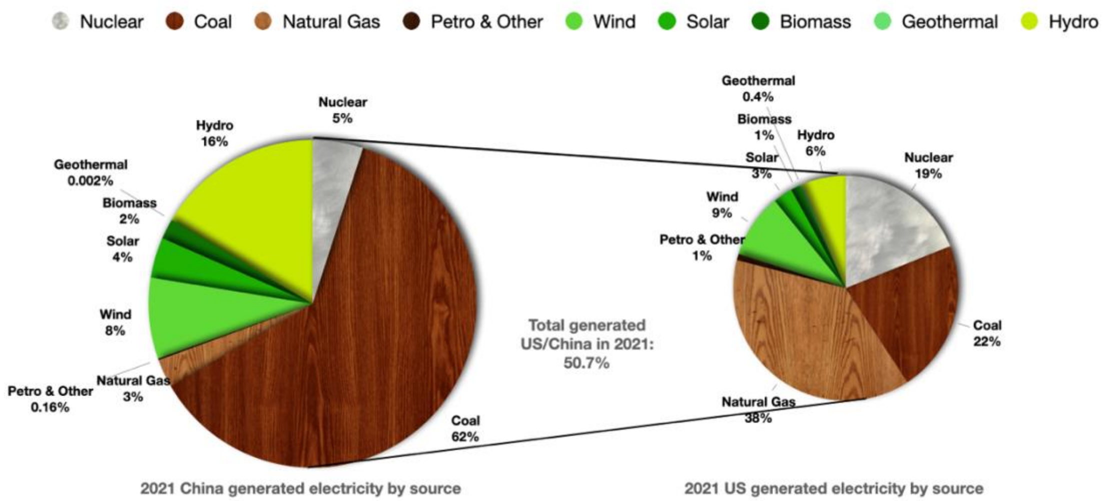


Figure 2 2021 US & China electricity generation details by sources

Fig.2: All brown colors represent different types of fossil fuel, and green colors represent different types of renewable energy. It can be seen that the combined weight of solar and wind-generated electricity is the same in both countries.

1.3 Comparability between the western area in China and the US

1.3.1 Western China and the western US boundary

The first step to comparing two regions is to define the boundary of the two regions. According to the area defined by the US Bureau of Labor and the National Bureau of Statistics of China (U.S. Bureau of Labor Statistics, 2014; National Bureau of Statistics of China (NBS), n.d.), 12 provinces in China and 11 states in the US have been categorized as western areas. Figure 3 and Figure 4 show each country's boundary of the western region. Although Inner Mongolia is a cross-north China province, it is categorized in the western area as its climate type is more similar to western China overall.

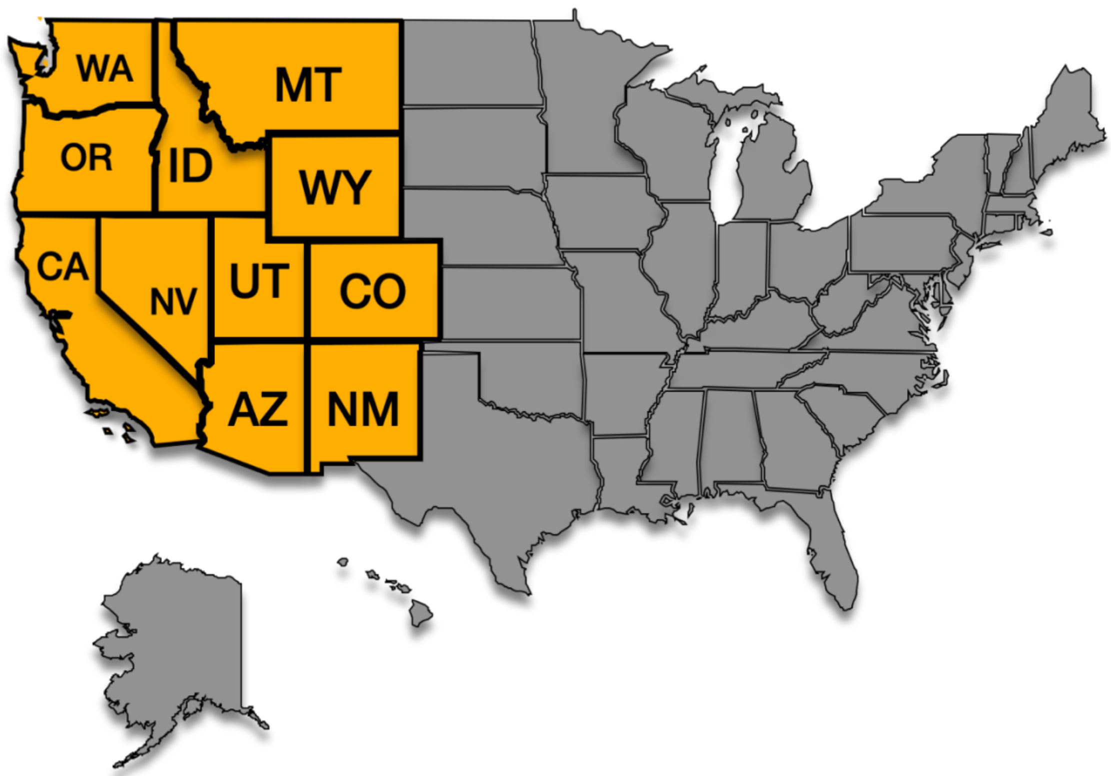


Figure 3 The boundary of the western US

Fig 3: Totally there are 11 states have been selected. The selected western regions in the US exclude overseeing states such as Alaska and Hawaii.

Figure 4 The boundary of western China

Fig 4: Totally 12 provinces have been selected in western China. Although some classifications only include western Inner Mongolia as the western area of China. In this study, the whole of Inner Mongolia will be included.

Thus, the selected 12 provinces are Xinjiang, Qinghai, Tibet, Gansu, Ningxia, Inner Mongolia, Sichuan, Chongqing, Guangxi, Guizhou, Yunnan, and Shaan Xi. On the other side, excluding the overseas territories, the rest of western stats of the US that based on US Bureau of Labor classification are Washington, California, Oregon, Nevada, Montana, Idaho, Wyoming, Utah, Colorado, New Mexico, and Arizona.

1.3.2 Similarities between two western regions

Area size

According to the central government of China, the total land area of China is 9.6 million square kilometers, and western China combined occupied more than 31.8% of national land size, about 3.1 million square kilometers (Government of China, 2005, n.d.). Comparably, the size of the US is about 9.2 million square kilometers, and the weight of the western US's size to its nation is 3.1 million square kilometers, about 31.5%. Thus, the weight of western US's land size is greater than western China.

Population density

Census data show that China and US will have 1,413 billion people and 331.9 million in 2021, respectively (datacommons, n.d.). Western China had 308 million, which took 21.9% of the national weight, and the western US took 21.5%. The weight of both regions' populations is very close.

Population density can be calculated accordingly using the area size of each western area. The western China population density is 56.61, and the value for the western US is 25.08. It can be concluded that the weight of the western population over its national value is the same for both western regions. However, regarding the population density, western China is twice as populated as the western US, which does not affect their comparability as the overall population of China is denser than the US.

GDP per capita

It is unreasonable to compare the two regions' absolute value of GDP per capita due to two countries are in different development phrase for now. However, their relative value of GDP per capita over its national data can be calculated and compared accordingly. In 2021, the total GDP of China was about ¥114,367 billion; by using the annual average exchange rate, which is ¥ 6.4529 RMB per USD, the total GDP of China in USD was $17.73 trillion.

$$GDP\ per\ capita = Real\ GDP/Population \qquad (1)$$

Given the population data mentioned above and the function (1) (GDP Per Capita Formula, 2021), the national GDP per capita in USD was about $12,547, and the western GDP per capita, using the GDP per capita of provincial-level data, was about $9,825, roughly 78.3% of the national GDP per capita. The value of the US GDP in 2021 was $23 trillion, and by using its total population and western population mentioned in the previous section, its national GDP per capita was $69,086. However, surprisingly the western area's GDP per capita was $70,153. Eventually, the western area's GDP per capita was higher than the national value, about 101.53%.

Western US GDP per capita was higher than its national GDP per capita because some well-known strong economic states, such as California and Washington, are located on the west coast. However, western China does not have such an advantage, and most of the under-developed provinces are located in western China, which was reasonable to see why west China's GDP per capita value was lower than the national GDP per capita. It can be concluded that, the economic level of the western US is stronger than the western China, by comparing with their national average scale.

Solar and wind potential

Both countries are the global leaders in renewable energy development and installation (IRENA, 2022). The considerable solar and wind technical potential in the western areas of both countries is likely to satisfy an outstanding share of national demand (University of Michigan, 2021 & WWF, 2014). The abundance of solar and wind natural resources is a priority before comparing solar and wind development in both regions. Figures 5 and 6 demonstrate both countries' solar and wind power densities. The highest potential of wind resources in China is located in the southwest and northern China, where most of these areas are categorized as western China.

Similarly, a tremendous amount of solar potential is distributed in northwest and southwest China. The US shared a similar distribution pattern for solar potential as China, the west, especially the southwest, has the best potential overall. The US wind potential is primarily located in the mid-west and northwest. The results show that both western China and the western US have natural advantages to generate enough green electricity to support their carbon neutrality target.

Given the similarities of all factors that both countries are sharing with, it can be concluded that western areas in both countries are suitable to make comparisons to conduct an assessment.

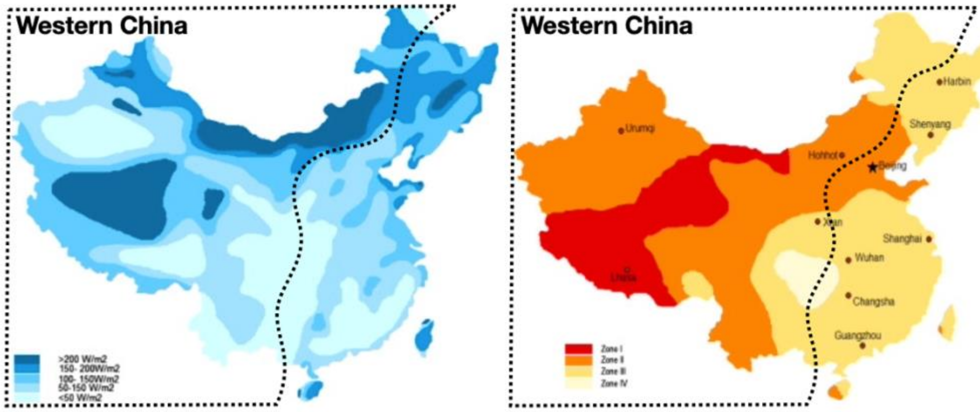


Figure 5 Distribution of effective solar and wind power density in 2008

Fig.5: Almost the most abundant solar and wind resources are distributed in China's western region. Most wind resources are distributed in northern China and Tibet, and most solar resources are distributed in northwest China and Tibet.

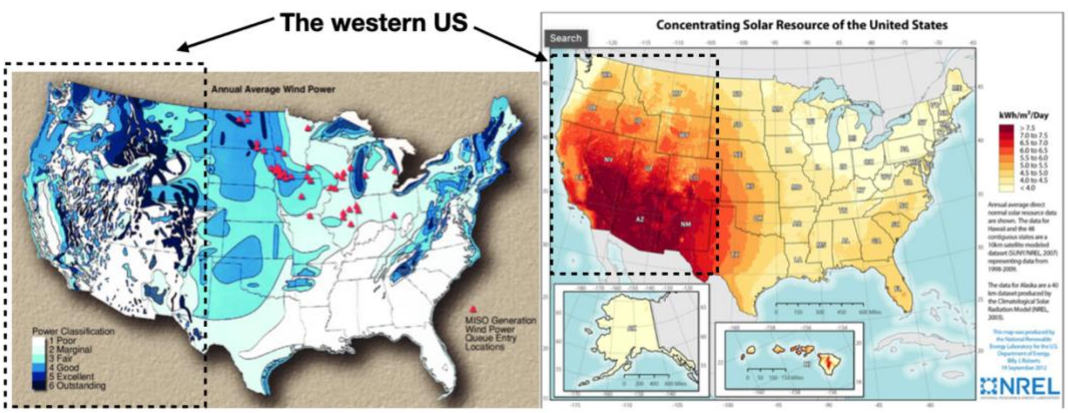


Figure 6 Solar and wind power map of the United States

Fig.6: Similarly, almost the most abundant solar and wind resources are distributed in the western region of the US. Northwest states have the highest level of wind resources. Southwest, the US has the most abundant solar resources.

1.4 Literature review

As carbon neutrality and renewable energy have become increasingly popular recently, many articles discuss wind and solar energy development from different perspectives. In general, for renewable energy development in China, from a national perspective, Bao & Fang (2013) and Liu et al. (2009) studied the potential and current development status of different types of renewable energy in China, Liu et al. (2009) conducted a review of historical solar energy development in China. In regional level, Wang & Cai (2007) and Wu & Xu (2013) explored the renewable energy development in northwest China; Hu et al. (2015) conducted a similar research in southwest China. Regarding studies focused on influencing factors of renewable energy, a multidimensional approach to the usage of renewable energy was introduced by Wang et al. (2020), which focused on a quantitative evaluation framework of different renewable energy sectors across 29 provinces in 7 years (starting from 2008). From previous studies, Wang et al., (2020) categorized five factors that potentially make an impact on China's renewable energy development given the existing literature, which are the economic foundation, policy and institutions, technological potential, energy security and environmental protection, and current status of the renewable energy sector. Among them, regarding articles assessed economic foundation and renewable energy development, besides annual official statistical reports such as the China Statistical Yearbook, Yearbook of China's Provinces and National Bureau of Statistics of China (NBS), Zhao & Luo (2017), Chen (2018), Sadorsky (2009), Lin & Moubarak (2014) and Lin et al. (2016) discussed the relationship between GDP per capita and renewable energy development. For articles that assess social policy factors, such as legislation and renewable energy policies, Shen & Luo (2015) and Liu (2018) critically reviewed existing policies' fallacies in China. Lo (2014) assessed China's technological development potential. Zhao & Luo (2017) and Zhang et al. (2017) discussed energy security and environmental protection. In summary, all influential factors listed above have academic reference to prove their significance in renewable energy development.

For the current status of wind and solar electricity development in China, Sahu (2017) provided a short review of wind energy developments in China, Zhang et al. (2020) did a cluster analysis for optimal allocation of onshore wind power in China, Lu et al. (2021) researched China's combined solar power and meanwhile provided recommendations to the storage's potential.

Parallelly, for the solar and wind electricity use and development status in the US, at the national level, Shaner et al. (2018) discussed geophysical constraints on the reliability of solar and wind power in the US, Krauland et al. (2021) assessed onshore wind resources potential across the United States. At the regional level, Frisvold et al. (2009) analyzed the relationship between solar energy and economics in Arizona. Short & Diskov (2012) matched western US electricity consumption with wind and solar resources. Other official reports published by National Renewable Energy Laboratory (NREL) also provided the background for the US wind and solar energy. Additionally, Bird et al. (2014) reported wind and solar energy curtailment in the US, and Hurlbut et al. (2017) discussed renewable energy transmission among states.

Comparatively, it is obvious that only limited articles discuss the differences between solar and wind in the western areas of both countries. But some scholars attempted to compared two countries as a whole: Lu et al. (2016) pointed out the challenges of developing wind power in China, compared with the US at the national level, Hurlbut et al. (2017) from NREL compared renewable energy cross-provinces transmission status between the US and China. Campbell compared China and the United States from a policy perspective, such as the green energy program and policies, in 2014. Bird et al. (2016) reviewed the international experience of wind and solar energy curtailment, including in China and the US.

1.4.1 Current research gaps

Many articles discuss the potential and problems that exist in developing solar and wind energy in China or the United States independently; however, limited literature attempts to compare the two countries solar and wind energy development together simultaneously. Nor conduct an applicable assessment framework for solar and wind energy, especially in the western area of the two countries, given their similarity in the similarity of natural conditions. Moreover, after China pledged the carbon peaking and carbon neutrality goal in 2020, previous literature neither focused on the lessons that western provinces in China could take from the comparable regions in other countries. Nor how to localize its solar and wind electricity to realize regional carbon neutrality.

Regarding the assessment framework for renewable energy, as mentioned previously, Wang et al. (2019) conducted a five-dimensional index to quantify renewable energy development in different provinces of China to assess their improved degree of renewable energy development performance and disparities level in renewable energy development across regions in past decades. The methodology applied has some similarities to this study. However, their research focused more on the internal comparison between each province in western, central, and eastern regions within China across different periods; additionally, the selected factors are different.

1.4.2 Objective, difficulties, and importance of the research

This study aims to assess solar and wind energy development in western China and the western United States. However, a few things could increase the difficulty by comparing these two regions directly. First, due to the two countries being in different development phases, it is unreasonable to use an area in a developed country to compare a region in a developed country. Second, solar and wind resources sharing some similarity but not the relative sea and land location. The western US has coastal areas but western China doesn't have coastal regions. California, Washington, and Oregon are three coastal states where western China has no provinces close to the ocean or as developed as California or Washington. Third, it is difficult to aggregate different factors' values, which are in different units, into an index to evaluate the overall performance of each province and state.

To avoid the above mentioned biases and difficulties to achieve the objective, this study designed a framework that uses the normalized weighted average score to rank each state's and province's performance by selecting each factor and conducting an aggregate value. The aggregate index of each individual represents their overall development performance in solar and wind energy. The exact method will be discussed in the methodology section.

The importance of this research is the first time evaluating two biggest emitters' western region in the world by using a relatively straightforward method to critically evaluate the two regions' performance and each individual's performance in solar and wind energy development. This framework also applicable to conduct an assessment of other renewable energy development, within a region or between regions, however, data of selecting factors need to be standardised. The results will conduct different insights by comparing in different directions; by using each western region's average effect to compare, representing the average numerical performance of two western regions, the two regions' development differences can be found accordingly. A vertical comparison can be conducted within a western area, either in west China or the western US, to see each province's or state's performance difference. Last but not least, a horizontal comparison can be used by only comparing the ranking result in each western region. The province and the state, which share the same ranking order, can be paired together, which represents, relatively, their solar and wind development status within each western region is the same. Also, in the future, provinces or states can use the same framework to get their latest ranking to conclude whether their performance has improved.

CHAPTER 2 METHODOLOGY

2.1. Selection of research target

This research initially aims to compare the consumption, use, and development of renewable energy between western China and the western US. However, due to the amount of the workload and needing main focus, this research then narrows down to one or two renewable energy. China Electricity Statistical Yearbook, China Electricity Statistics Compilation, and US Electrical Power Annual are the most authoritative and comprehensive electricity data base in both countries, and which are also the major source of data used in this study. Their statistics include five categories of renewable energy: wind, solar, hydropower, biomass, and geothermal. Hydropower is the largest renewable in the world and generates more electricity than solar and wind combined. Both countries have well-developed it compared to other renewable energy (Brigham, 2022; China Electricity Statistical Yearbook, 2020; Electric Power Annual 2021 - EIA, 2020). Thus, the potential of hydropower, in the future, is relatively limited compared with the rest. Although biomass and geothermal might have tremendous potential, both generated negligible amount of electricity in both countries until 2021. Specifically, data from China Electricity Statistical Yearbook and US Electrical Power Annual shows that electricity powered by geothermal only occupied 0.002% in China and 0.4% in the US; moreover, electricity powered by biomass only occupied approximately 2% in China and 1% in the US, respectively (China Electricity Statistical Yearbook, 2020, Electric Power Annual 2021 - EIA, 2020). Eventually, solar and wind have been filtered out among all renewable energy, which also have been rapidly developed in both countries in the past decades. The breakdown of electricity contribution, having introduced in section 1.2, by different energy resources in both countries is shown in Figure 1.

In this case, the research topic narrowed down to the comparison regarding the consumption, use, and development of solar and wind energy between western China and the western US. The research direction then shifts further as the breakdown of solar and wind-powered electricity consumption data would be difficult to obtain at the community level. Additionally, the consumers of electricity, such as business owners or residents, lack selection ability when they consume electricity, as electricity is a unique commodity. For example, regardless of the country consumers live in, they can only consume solar or wind-powered electricity when their only electricity source is from the public electricity grid. When different sources generate electricity, they all mix and connect to the electricity grid, so the users eventually consume the weighted average of all types of electricity. The nature of electricity is that people cannot distinguish the difference when they are in the same "pool" unless they only consume electricity from their generation system, such as solar panels on the roof to power a house. Given the unstable nature of distributed solar and wind resources, as they are highly dependent on the weather conditions, most families or residential owners would connect to the public grid system. Eventually, all such individual demand centres can still not calculate the exact amount of solar and wind-generated electricity, but the same as the provincial or national average percentage. After including this factor, the research topic was narrowed down one more time: comparing solar and wind power development between western China and the western US (at provincial and state levels).

2.2 Methodology

2.2.1 Selection of influencing factors

Given the broadness of influencing factors, only limited factors are selected to conduct this assessment, so the selection of influential factors play a significant role in the final result. A framework has been designed to evaluate each province and state by using selected data. There are five critical steps during the solar and wind generation process: installation, generation, grid connection, transmission, and consumption (Grid-Connected Renewable Energy Systems, n.d.). In this paper, these five key steps are defined as inside factors. Specifically, located at the supply centre, such as solar or wind farms, wind or solar panels must be installed first. After panels have been installed appropriately, then they start to generate electricity. Next, they need to connect to the public electricity grid to transmit the generated electricity to load centres. Besides the inside factors influencing the performance during the electricity generation cycle, outside factors, such as economic and social-political factors, on the other hand, also play critical roles in each country's solar and wind power development. Together, there are seven key factors will be included in the framework.

As selected factors are too general to assess, sub-factors of each selected factor also need to be identified. For outside factors, as the economic factor typically indicates an area's affluence or economic development level, GDP per capita and disposable income per capita would be chosen to collectively indicate the value of the economic factor. The advantage of using per-capita value is to avoid the bias of population difference across different provinces and states in two countries. Additionally, all currency units need to be converted into US dollars by using the average annual exchange rate. As most social policy factors are qualitative data and it would be challenging to conduct an unbiased parallel comparison across two countries, this paper only selects solar and wind incentives implemented by each province and states to represent social policy factor. Due to there is no official renewable energy incentives catalogue in China, this study will follow the standard categorized by *Database of State Incentives for Renewables & Efficiency*. According to the *Database of State Incentives for Renewables & Efficiency* (Database of State Incentives for Renewables & Efficiency®, 2022), the database categorized solar and wind incentives into six categories: loan programs, rebate programs, corporate tax credits, personal tax credits, property tax credits, and net metering. Thus, the existence of these six incentives in a state or province would be used to represent social policy factors.

For inside factors, the 5-year average new installation ratio and the cumulative installation capacity (until 2020) for both solar and wind are sub-factors of installation. The reason to use a 5-year average is to avoid the fluctuation of installation speed as much as possible. For example, a state may only install limited solar panels in a selected year well below the average installation speed, but a 5-year average can indicate a trend. Additionally, the advantage of ratio instead of the actual number, which is the increasing percent rather than installation capacity, is to avoid timing bias. For example, without other exceptional circumstances, California would install more solar panels than Idaho, in an absolute capacity value, given that its land size and population are significantly more prominent, making the demand more significant. Thus, using the ratio instead of absolute value could avoid this problem. Another sub-factor, the cumulative installation capacity (until 2020), represents the total capacity the state has installed, which can indicate the total efforts this area has made.

Next, selecting the percentage of total generated electricity comes from wind and solar resources to indicate the generation factor due to some states or provinces may have vast amounts of installation, however, whether such a massive amount of cumulative installation has been used correctly and efficiently to help this province or state towards carbon neutrality is the key to evaluate. Additionally, using the relative ratio can also make an unbiased comparison regardless of the absolute amount of total capacity that different provinces or states can generate.

The selected sub-factor or the third factor is the solar and wind curtailment rate. After facilities have been installed and generating electricity, all generators need to connect to the grid to transmit electricity to the other location. However, in real life, as the unstable nature of solar and wind resources, not all electricity generated by solar and wind is able to connect to the grid, and the percentage which is not able to connect to the grid is the curtailment capacity. Unfortunately, given that the statistical standard regarding curtailment data differs in both countries, the US only counted curtailment rates based on its electric system and some of the US electric systems across several states. Figure 23 is a basic map of the US electric system (Micek, 2022). Besides, the solar and wind curtailment data accuracy is very vague in both countries, especially considering the breakdown of solar and wind curtailment data such as curtailment rate of solar PV and solar thermal, and curtailment rate of offshore wind and onshore wind) over the past few years. Thus, this study will assume solar, wind curtailment is no longer a primary concern for both western regions.

Three sub-factors have been selected for the transmission factor as its contributors: transmission loss, reliability and export and import status. After green electricity connecting to the grid, the percentage it can successfully transmit to load centres is the critical success factor. The transmission process requires the electricity grid to be reliable and flexible. Export and import status demonstrates the sufficiency of electricity that the state or province can help itself and the amount it could sell to the other states or provinces, which also rely on grid infrastructure.

Last but not least, the sub-factor of the consumption factor is the energy deficit index. Unlike export and import status, the energy deficit index evaluates the independency of electricity that a province could generate, however, without considering transmission factors' influence. The following function calculates the electricity deficit index based on the function used by Wang et al. (2020)’s study:

$$D = C/G \tag{2}$$

Where D is the electricity usage deficit, C is the annual total consumption, and G is the total annual generation.

A summary of the assessment framework table is listed below in Figure 7. The above part is the outside factors and their sub-factors, and the inside and inside sub-factors are below.

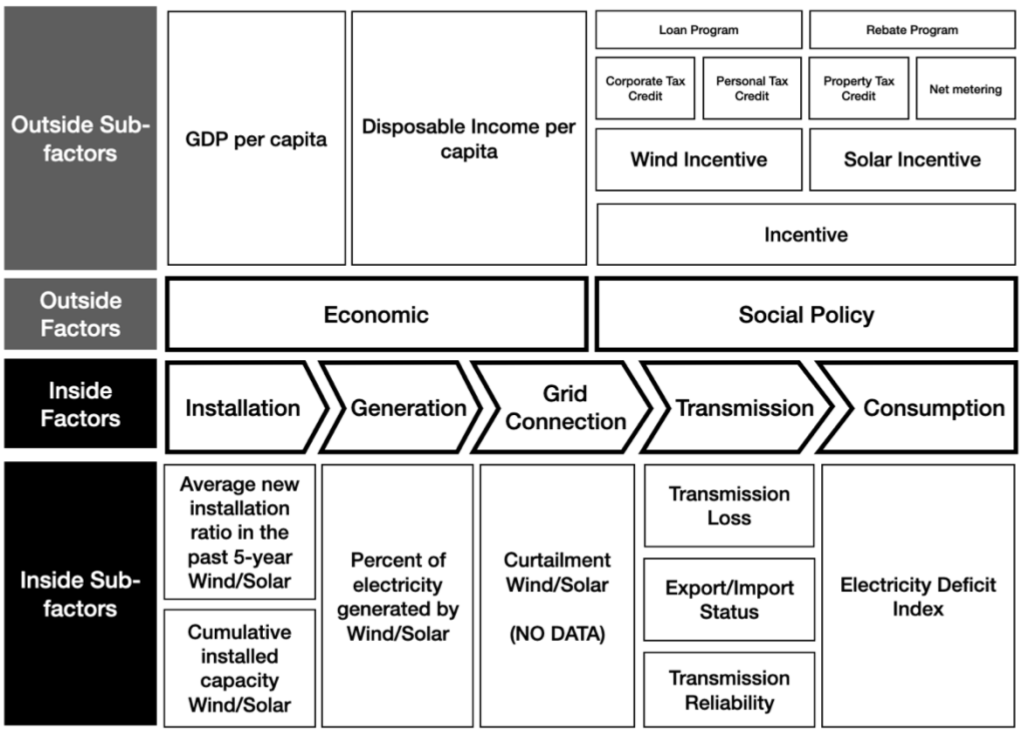


Figure 7 Solar and wind energy assessment framework for each province and state

Fig. 7: All selected influential factors are listed above. Although the grid-connection factor is important for assessing solar and wind development, however, due to the boundary of the electric system in the western US is not the same as the state boundary, the state-level curtailment data is not able to collect

2.2.2 Data Collection

Table 1 shows the summary table for the source of sub-factors data. For inside sub-factors, most western China data were cited from the 2020 China Electricity Statistical Yearbook, published by the National Energy Administration of China, and the 2019 and 2020 Compilation of National Electricity Industry Statistics, which the China Electricity Council publishes. For US data, most of the western US data were cited from the 2020 Electric Power Annual, published by Energy Information Administration. For outside sub-factors, the economic data were published by the China National Bureau of Statistics and the US Bureau of Economic Analysis; additionally, social policy data were sourced from the National Energy Administration of China and the US Database of State Incentives for Renewables and Efficiency.

Table 1 Data source of applied sub-factors in the assessment framework

Table 1
Data source of applied sub-factors in the assessment framework

Classification	Factors	Sub-factors	Year	Sources-China	Sources-US
Outside	**Social Policy (Incentiv**	Corporate tax Credit	*Until 2022*	*NEA*	*Database of State Incentives*
		Personal tax credit	*Until 2022*		
		Loan program	*Until 2022*		
		Rebate program	*Until 2022*		
		Property tax	*Until 2022*		
		Net metering	*Until 2022*		
Outside	**Economics**	GDP per capita ($USD)	*2020*	*China National Bureau of Statistics*	*Bureau of Economic Analysis*
		Disposable income per capita ($USD)	*2020*		
Inside	**Installation**	Cumulative installed capacity (Wind & Solar)	*Until 2020*	*China Electricity Statistical Yearbook; Compilation of National Electricity Industry Statistics*	*EIA*
		2015-2020 average new installation ratio (Wind & Solar)	*2015-2020*	*China Electricity Statistical Yearbook; Compilation of National Electricity Industry Statistics*	
Inside	**Generation**	2020 percent of electricity generated by wind & solar	*2020*	*Compilation of National Electricity Industry Statistics*	*EIA*
Inside	**Grid Connection**	2015-2020 average curtailment for wind & solar	*N/A*	*N/A*	*N/A*
Inside	**Transmission**	2020 transmission loss	*2020*	*Compilation of National Electricity Industry Statistics*	*EIA*
		2020 transmission reliability	*2020*		
		2020 export & import status	*2020*		
Inside	**Consumption**	2020 Electricity deficit Index	*2020*	*Compilation of National Electricity Industry Statistics*	*EIA*

Table 1: The table indicates the data table of selected factors and their sub-factors used in this study. All sources and years are indicated above.

2.2.3 The critical assumption and calculation in the assessment Framework

After all factors and their sub-factors have been selected and data have been collected accordingly, a final assessment function can be developed as (3)

$$N_{score} = \sum W_x * N_x \ (W>0; N>=0) \quad (3)$$

Where **Nscore** represents the normalized aggregate solar & wind development performance score for a province or state, all Wx represents the weight of factors, and all Nx represents the normalized value for different factors. Based on the selection of factors and sub-factors in the previous section, the function can be rewritten as (4):

$$N_{score} = W_e*N_e + W_s*N_s + W_i*N_i + W_g*N_g + W_{gc}*N_{gc} + W_t*N_t + W_c*N_c \ (W>0; N>=0) \quad (4)$$

Specifically, for weight parameters, We represents the normalized economic score, Ws represents the weight of normalized social policy score, Wi represents the weight of normalized installation score, Wg represents the weight of normalized generation score, Wgc represents the weight of normalized grid connection score, Wt represents the weight of normalized transmission score, and Wc represents the weight of normalized consumption score. Additionally, for normalized value parameters, Ne represents the normalized economic score, Ns represents the normalized social policy score, Ni represents the normalized installation score, Ng represents the normalized generation score, Ngc represents the normalized grid connection score, Nt represents the normalized transmission score, and Nc represents the normalized consumption score.

To calculate the final score, ***Nscore***, each factor's normalized value should be by their sub-factors normalized value first, and the function of all factors can be found from (5) to (10)

$$N_e = V_{gdp} * N_{gdp} + V_{income} * N_{income} \quad (5)$$

$$N_s = V_{Rebate} * N_{Rebate} + V_{Net\ Metering} * N_{Net\ Metering} + V_{PPtax} * N_{PPtax} + V_{Ctax} * N_{Ctax} + V_{income} * N_{income} \quad (6)$$

$$N_i = V_{5\text{-year\%Ins-wind}} * N_{5\text{-year\%Ins-wind}} + V_{5\text{-year\%Ins-solar}} * N_{5\text{-year\%Ins-wind}} + V_{cwind} * N_{cwind} + V_{csolar} * N_{csolar} \quad (7)$$

$$N_g = V_{\%\_Gwind} * N_{\%\_Gwind} + V_{\%\_Gsolar} * N_{\%\_Gsolar} \quad (8)$$

$$N_{gc} = V_{curtail\text{-}wind} * N_{curtail\text{-}wind} + V_{curtail\text{-}solar} * N_{curtail\text{-}solar} \quad (9)$$

$$N_t = V_{trans\_loss} * N_{trans\_loss} + V_{trans\_Reliability} * N_{trans\_Reliability} + V_{export\_import} * N_{export\_import} \quad (10)$$

$$N_c = V_{consumption} * N_{consumption} \quad (11)$$

V>0 and N>=0 apply to all functions above

Like function (4), where all Vx represents the weight of sub-factors, and all Nx represents normalized value for different sub-factors. For weight parameters, Vgdp represents weight of GDP per capita, Vincome represents weight of disposable income per capita, VCtax represents weight of corporate tax credit, VPStax represents weight of personal tax credit, VPPtax represents weight of property tax credit, VRebate represents weight of rebate, VNet Metering represents weight of net metering, V5-year%Ins-wind represents weight of 2015-2020 average new installation ratio for wind, V5-year%Ins-solar represents weight of 2015-2020 average new installation ratio for solar, Vcwind represents weight of cumulative installed capacity wind, Vcsolar represents weight of cumulative installed capacity solar, V%_Gwind represents weight of 2015-2020 average wind curtailment rate, V%_Gsolar represents weight of 2020 Percent of electricity generated by solar, Vcurtail-wind represents weight of 2015-2020 average wind curtailment rate, Vcurtail-solar represents weight of 2015-2020 average solar curtailment rate, Vtrans_loss represents weight of transmission loss, Vtrans_Reliability represents weight of transmission reliability, Vexport_import represents weight of export/import status, and Vconsumption is the weight of 2020 electricity deficit index. For normalized value parameters, GDP represents normalized GDP per capita.

For normalized value parameters, Ngdp represents normalized GDP per capita, Nincome represents normalized disposable income per capita, NCtax represents normalized corporate tax credit, NPStax represents normalized personal tax credit, NPPtax represents normalized property tax credit, NRebate represents normalized rebate, NNet Metering represents normalized net metering, N5-year%Ins-wind represents normalized 2015-2020 average new installation ratio for wind, N5-year%Ins-solar represents normalized 2015-2020 average new installation ratio for solar, Ncwind represents normalized cumulative installed capacity wind, Ncsolar represents normalized cumulative installed capacity solar, N%_Gwind represents normalized 2020 Percent of electricity generated by wind, N%_Gsolar represents normalized 2020 Percent of electricity generated by solar, Ncurtail-wind represents normalized 2015-2020 average wind curtailment rate, Ncurtail-solar represents normalized 2015-2020 average solar curtailment rate, Ntrans_loss is normalized transmission Loss, Ntrans_Reliability is normalized transmission reliability, Nexport_import is normalized export/import status, and Nconsumption is normalized 2020 electricity deficit index.

2.2.4 Normalization

Since the value of all sub-factors are in different units and more-or-less uniformly distributed across a fixed range, to calculate the final ***Nscore*** for each province or state by using the function from (4) to (11), all data need to be normalized first. Furthermore, the function of normalization should use the function (12).

$$X' = (X - X_{min})/(X_{max} - X_{min}) \quad (12)$$

According to function (2), where the energy deficit is calculated by using electricity consumption over electricity supply in a province or a state, the higher the value is, the less electrical independence the region has. Moreover, since function (3) or (4) defines the final development score as the weighted average of different factors, this study considers that the less the electricity deficit value is, the higher the score a province or state should be assigned. Thus, the normalization method would be different from function (12) but function (13), which would automatically assign a negative value for an area with higher consumption than its supply.

$$N_{consumption} = \mathbf{(1 - D)} \tag{13}$$

Where D is the electricity deficit value previously calculated in function (2)

2.2.5 Weight assumption

As in this study, no significant evidence shows that a different weight should apply parameters that contribute to sub-factors or factors. Thus, it is reasonable to assume all weights should be the same. However, in future study, it is also applicable by using different weight in the model if necessary.

Moreover, the function above would change to below after all weight parameter equals one:

$$N_{score} = N_e + N_s + N_i + N_g + N_{gc} + N_t + N_c \quad (W>0;\ N>=0) \tag{14}$$

$$N_e = N_{gdp} + N_{income} \tag{15}$$

$$N_s = N_{Rebate} + N_{Net\ Metering} + N_{PPtax} + N_{Ctax} + N_{income} \tag{16}$$

$$N_i = N_{5\text{-}year\%Ins\text{-}wind} + N_{5\text{-}year\%Ins\text{-}wind} + N_{cwind} + N_{csolar} \tag{17}$$

$$N_g = N_{\%\_Gwind} + N_{\%\_Gsolar} \tag{18}$$

$$N_{gc} = N_{curtail\text{-}wind} + N_{curtail\text{-}solar} \tag{19}$$

$$N_t = N_{trans\_loss} + N_{trans\_Reliability} + N_{export\_import} \tag{20}$$

$$N_c = N_{consumption} \tag{21}$$

$$N_{score} = N_{gdp} + N_{income} + N_{Rebate} + N_{Net\ Metering} + N_{PPtax} + N_{Ctax} + N_{income} + N_{5\text{-}year\%Ins\text{-}wind} + N_{5\text{-}year\%Ins\text{-}wind} + N_{cwind} + N_{csolar} + N_{\%\_Gwind} + N_{\%\_Gsolar} + N_{curtail\text{-}wind} + N_{curtail\text{-}solar} + N_{trans\_loss} + N_{trans\_Reliability} + N_{export\_import} + N_{consumption} \tag{22}$$

2.2.6 Applying data to the assessment framework

Figure 8 shows the calculation process of each normalized value. Adding the aggregate normalized outside factor's value and the aggregate normalized inside factor's value together would produce the final development score for each province and state.

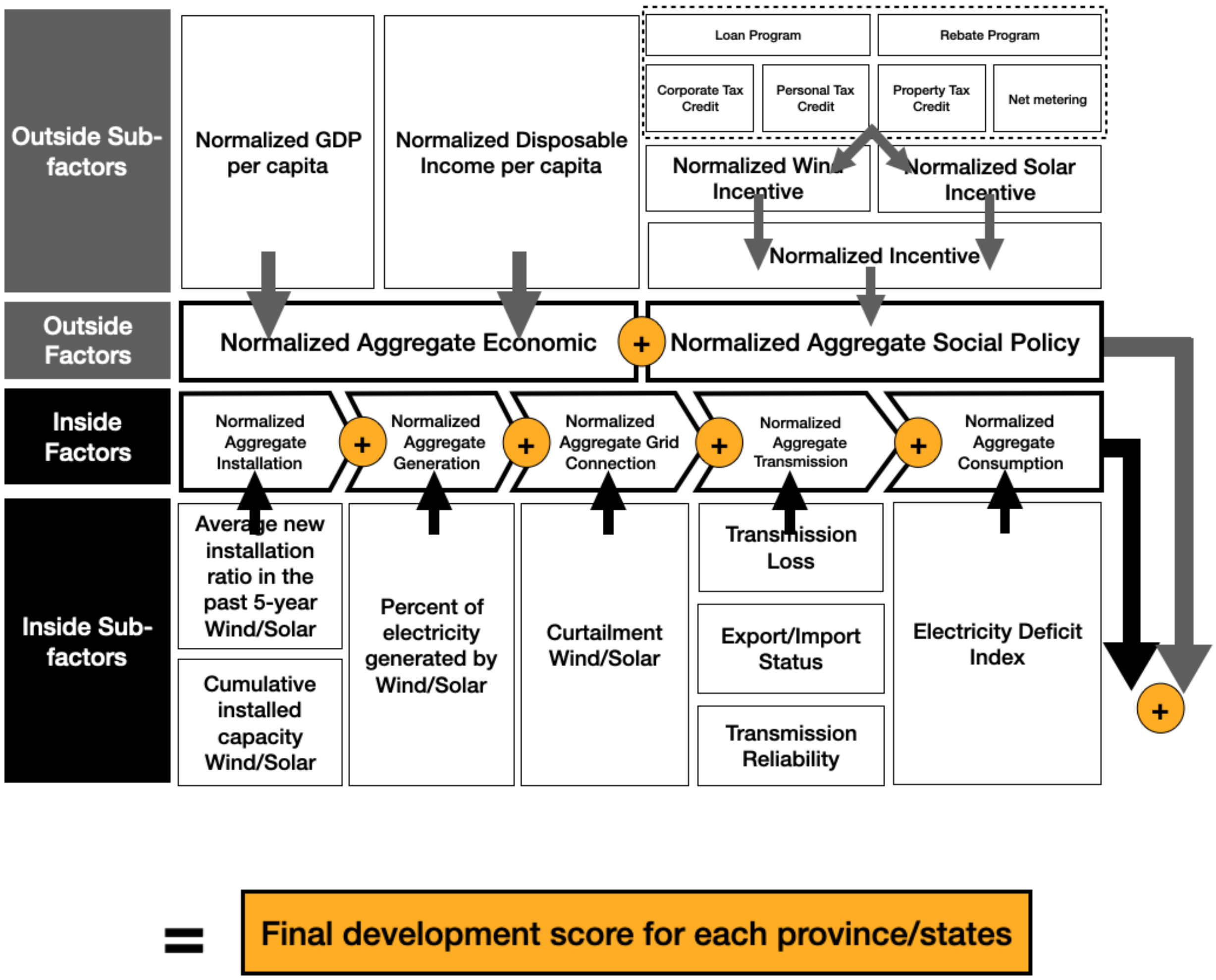


Figure 8 Assessment framework application process

Fig.8: The calculation flow in this assessment framework shows above. All factors are calculated by adding their sub-factors' normalized value. The final score is calculated by adding the factors' normalized score.

CHAPTER 3 SOLAR AND WIND PERFORMANCE IN WESTERN US AND WESTERN CHINA

3.1 Normalized result of outside factors

Economics

The economic factor is an aggregate value of the normalized GDP per capita index and normalized disposable income per capita. Figure 9 and figure 10 show the absolute value of GDP per capita and disposable income of each unit in both western states in 2020, respectively. For both sub-factors, by only comparing their absolute value, it is clear that the western US's economic power is significantly greater than western China. Additionally, by comparing each western region's sub-factor average value to their national average, the western US' GDP per capita is closer to the national average but still lower. Regarding the regional average disposable income, both western regions share a similar weight. This study will not directly compare each unit's absolute value in each region. Instead, each region will process standardization separately to avoid bias, and the aggregate normalized economic result shows in figure 11.

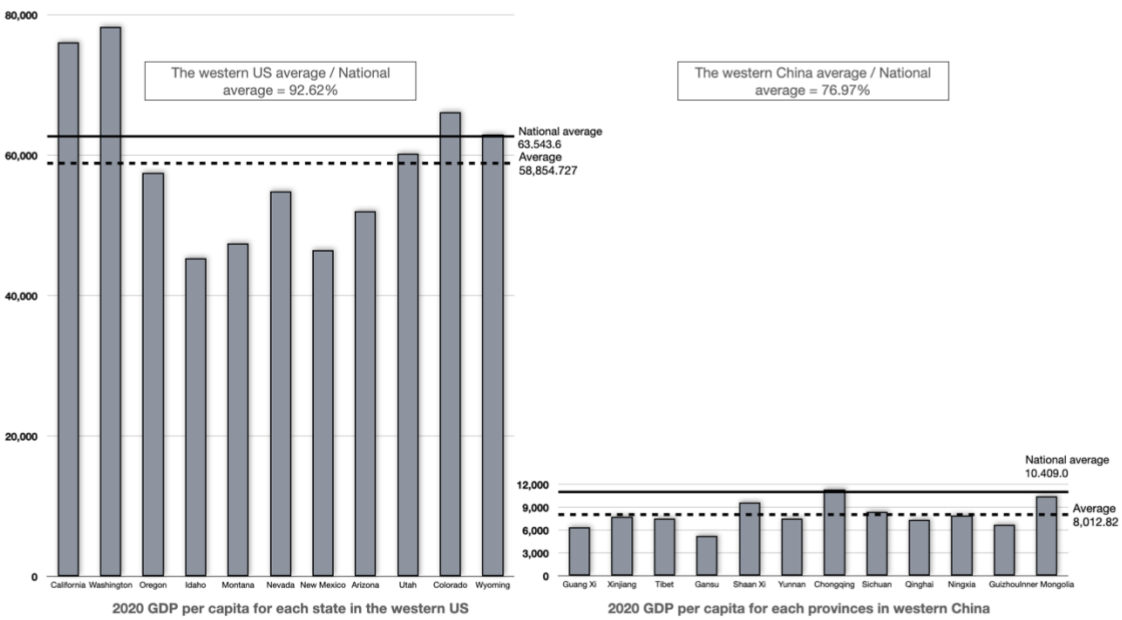


Figure 9 2020 GDP per capita in each province and state

Fig.9: In 2020, the GDP per capita of western states is significantly higher than the value in western China. However, the western US average is closer to the national average.

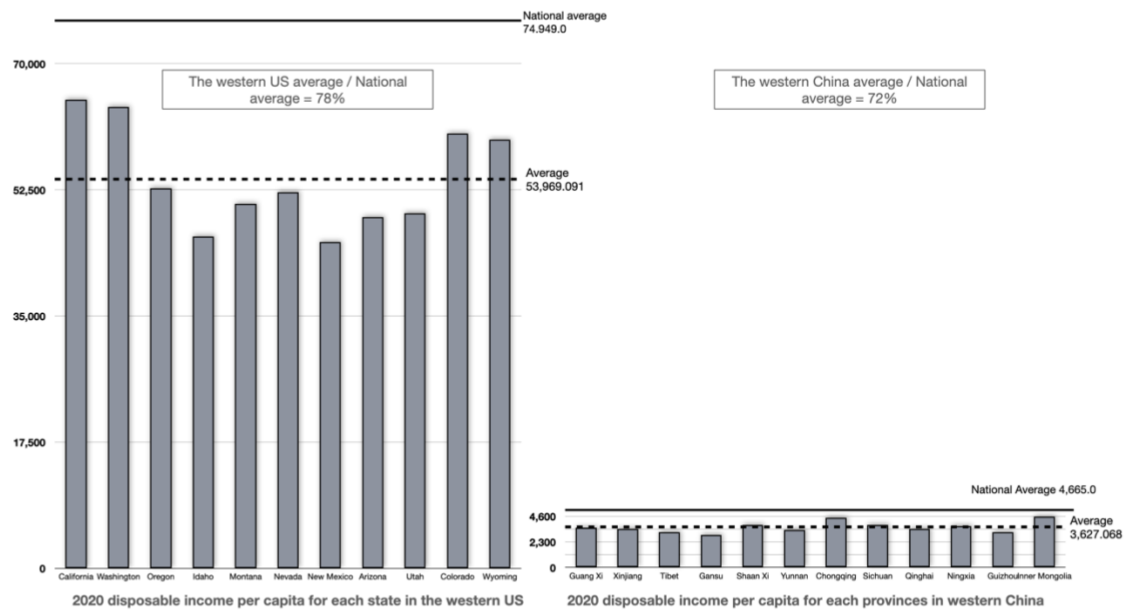


Figure 10 2020 disposable income per capita in each province and state

Fig.10: The same trend can be found in disposable income. The average disposable income of the western US is about 78% of the national average, and a similar ratio can also be found for China, about 72%.

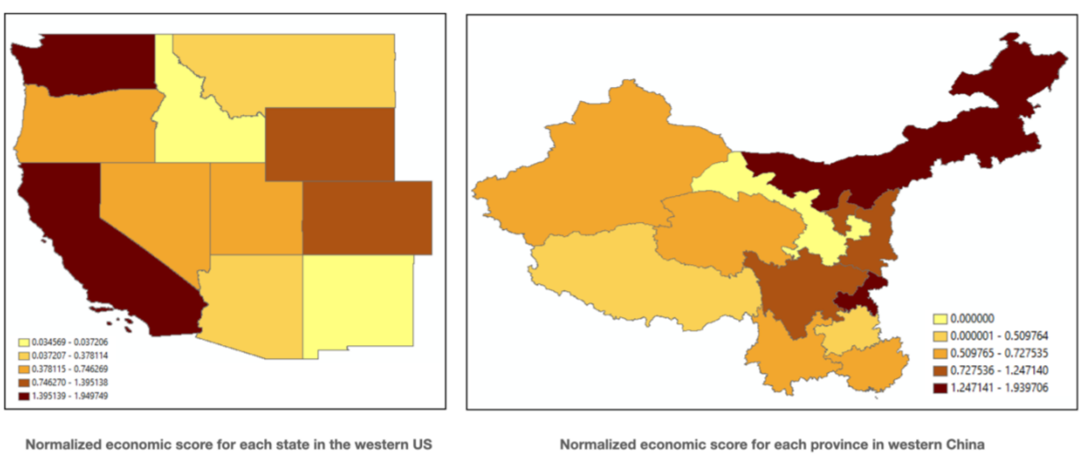


Figure 11 Normalized economic score

Fig.11: California and Washington have the strongest economic performance. Chongqing and Inner Mongolia are top two in the western China.

Social policy (incentives)

Similarly, the social policy factor is an aggregate value of six normalized incentives based on their existence in each province or state. Since the effectiveness of incentives is hard to quantify, so it is more reasonable to only assign 0 and 1 to each incentive based on their existence. Solar and wind incentives scores are conducted separately, and their results are shown in table 2 and table 3. Since the higher the incentive score indicates the more options available for solar and wind users and consumers, both regions will process the normalization process collectively. All western provinces in China have an identical amount of incentives in both solar and wind, and all of their aggregate value is less than the minimum value of the western US. Eventually, the normalized social policy score is shown in figure 12.

Table 2

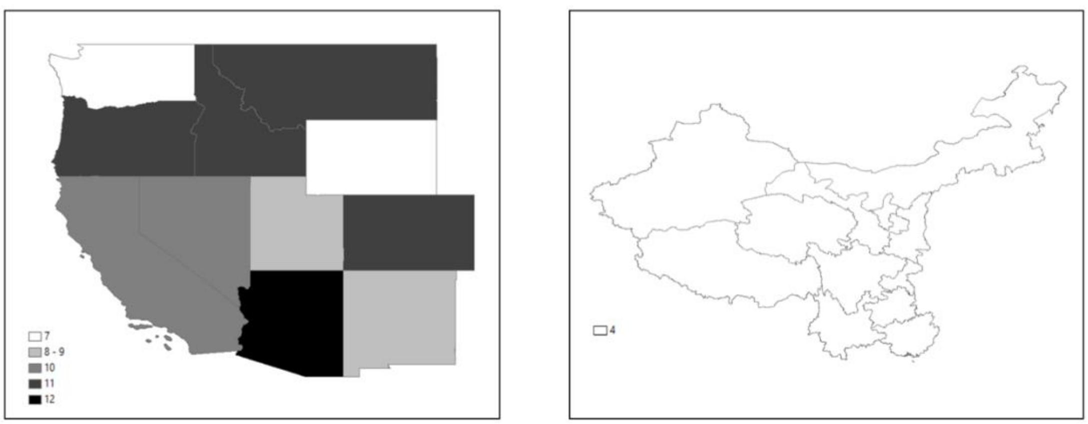
Wind incentives in the western US and westenr China

	Corporate tax credit	Personal tax credit	Property tax incentive	Net metering	Loan program	Rebate program	Σ
Provinces in western China							
Guangxi	0	0	0	1	1	0	2
Xinjiang	0	0	0	1	1	0	2
Tibet	0	0	0	1	1	0	2
Gansu	0	0	0	1	1	0	2
Shaanxi	0	0	0	1	1	0	2
Yunnan	0	0	0	1	1	0	2
Chongqing	0	0	0	1	1	0	2
Sichuan	0	0	0	1	1	0	2
Qinghai	0	0	0	1	1	0	2
Ningxia	0	0	0	1	1	0	2
Guizhou	0	0	0	1	1	0	2
Inner Mongolia	0	0	0	1	1	0	2
Provinces in the western US							
California	1	0	0	1	1	1	4
Washington	1	0	0	1	1	0	3
Oregon	1	0	1	1	1	1	5
Idaho	1	1	1	1	1	0	5
Montana	1	1	1	1	1	0	5
Nevada	1	0	1	0	1	1	4
New Mexico	1	1	0	1	1	0	4
Arizona	1	1	1	1	1	1	6
Utah	1	1	0	1	1	0	4
Colorado	1	1	1	1	1	1	6
Wyoming	1	0	0	1	1	0	3

Table 3
Solar incentives in the western US and westenr China

	Corporate tax credit	Personal tax credit	Property tax incentive	Net metering	Loan program	Rebate program	Σ
Provinces in western China							
Guangxi	0	0	0	1	1	0	2
Xinjiang	0	0	0	1	1	0	2
Tibet	0	0	0	1	1	0	2
Gansu	0	0	0	1	1	0	2
Shaanxi	0	0	0	1	1	0	2
Yunnan	0	0	0	1	1	0	2
Chongqing	0	0	0	1	1	0	2
Sichuan	0	0	0	1	1	0	2
Qinghai	0	0	0	1	1	0	2
Ningxia	0	0	0	1	1	0	2
Guizhou	0	0	0	1	1	0	2
Inner Mongolia	0	0	0	1	1	0	2
Provinces in the western US							
California	1	1	1	1	1	1	6
Washington	1	1	0	1	1	0	4
Oregon	1	1	1	1	1	1	6
Idaho	1	1	1	1	1	1	6
Montana	1	1	1	1	1	1	6
Nevada	1	1	1	1	1	1	6
New Mexico	1	1	1	1	1	0	5
Arizona	1	1	1	1	1	1	6
Utah	1	1	0	1	1	1	5
Colorado	1	1	1	0	1	1	5
Wyoming	1	1	0	0	1	1	4

Table 2&3: Tables above show that the wind and solar incentive score for each western province and state, respectively. If the selected incentives currently exist in that province or state, a value one would be grated. Otherwise, a value of 0 would be assigned to that incentive category.



Normalized social policy score for each state in the western US

Normalized social policy score for each province in western China

Figure 12 Normalized social policy score

Fig.12: Results of the normalized social policy score. All western provinces in China are identical as 4, which is smaller than the minimum value of the western US.

3.2 Normalized result of inside factors

Installation

The normalized installation score is composed of two sub-factors which are cumulative installation capacity in thousand Mwh and the average installation speed in the past 5-year. The final installation score is calculated by adding the normalized score of two subfactors of solar and wind together. Figure 13 shows the normalized installation score and each sub-factor performance.

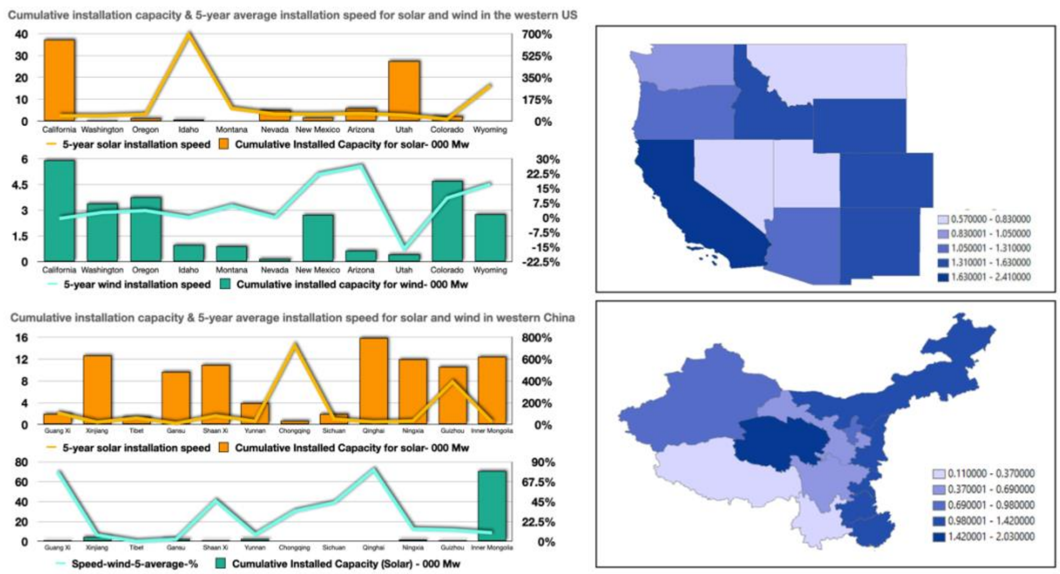


Figure 13 Normalized installation score

Fig.13: Orange color represents the solar energy and green color represents the wind energy. Line charts represents the average installation speed in the past five year of each provinces.

Generation

Figure 14 below indicates the generation score in both regions, calculated by the normalized value of the total percent of generated electricity from solar and wind resources.

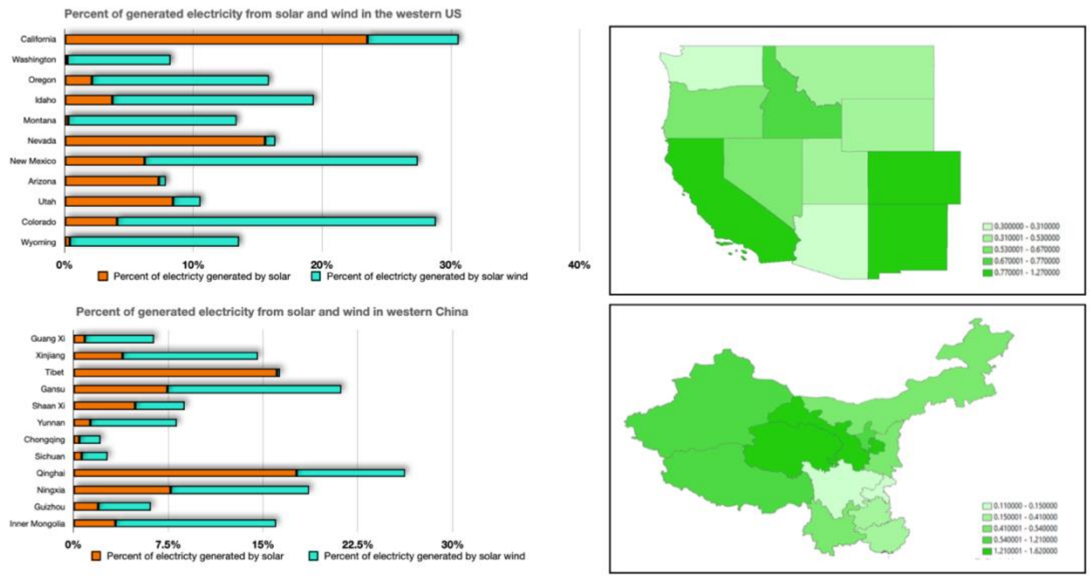


Figure 14 Normalized generation score

Fig.14: Stacked bar chats represents the combined weight of solar and wind generated electricity in total generated electricity. California, Colorado and New Mexico are the top three states which are close to 30%. Qinghai, Gansu and Ningxia are the top three in western China.

Transmission

The normalized transmission score comprises three sub-factors: transmission reliability, transmission loss, and electricity import and export capacity. Details are shown in figure 15 below. For transmission reliability, given that the statistical standard is different in both countries, the transmission reliability score in both regions is not able to be compared directly. However, it needs to normalize within each region first.

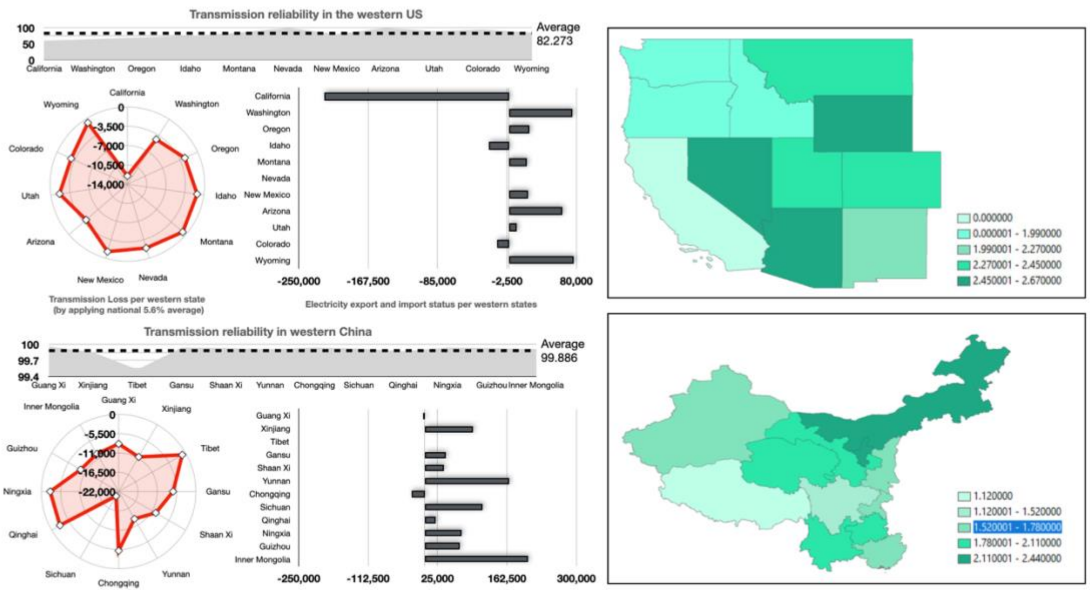


Figure 15 Normalized transmission score

Fig.15: California has the lowest transmission reliability and has the highest transmission loss, potentially due to its population (as demand is high), and has three electric systems.

Consumption

Last but not least is the consumption score which is solely dependent on the energy deficit score. The bar, which represents in red color, indicates that the state or province consumes more electricity than it generates, which means the electricity independence is low. Figure 16 below shows the detail. It can conclude that the western US's electricity intendancy, overall, is lower than western China.

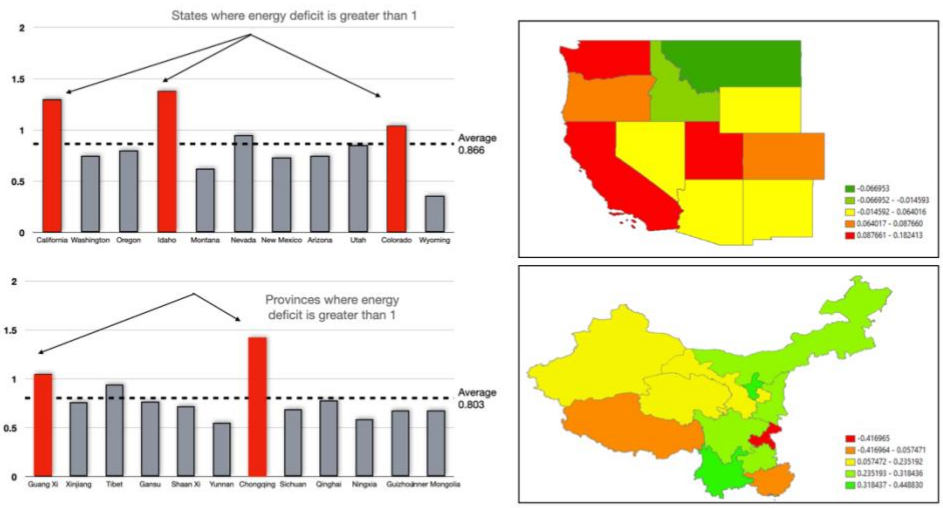


Figure 16 Normalized consumption score

3.3 Normalized final results

Figure 17 below shows the final normalized performance score in both regions. The darker colour of an area is, the better performance it has.

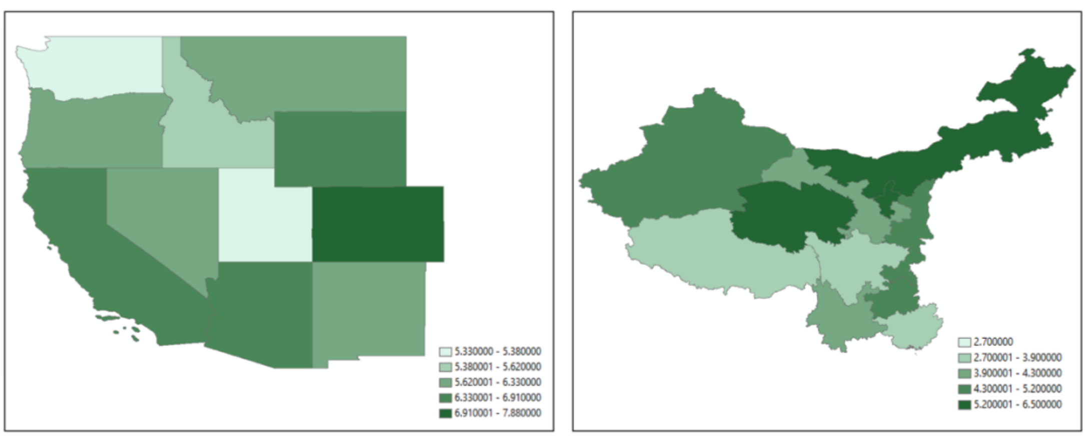


Figure 17 Normalized solar and wind performance score

Fig.17: Colorado and Inner Qinghai are the top performer in both western regions.

CHAPTER 4 UNDERSTANDING THE RESULT: THREE WAYS COMPARISON

4.1 Overall comparison

Table 4 shows that the average normalized score in the western US is better than the score in western China, about 1.54, which is majorly caused by the social policy difference shown in Figure 18 below. The standard deviation values of 11 western US states and 12 western China are 0.72 and 1.09, respectively, which shows that solar and wind development status in both western areas are relatively similar but states in the western US are more even.

As mentioned in the methodology section, the normalized social policy score is an aggregate normalized value of six different incentives for solar and wind. For simplicity, regardless of the quantities of incentives that exist under the category, if its existence can be confirmed, then a value of 1 would be assigned. For example, California has a corporate tax credit program. However, it does not have a tax credit program for wind installation; thus, in California, a value of 1 would be assigned to the corporate tax credit, and a value of 0 would be assigned to the tax credit program for wind installation. All provinces in western China have identical incentives. It needs to catch up to the US due to the lack of a personal tax credit program, corporate tax credit program, property tax program, and rebate program for both solar and wind. Western China has a net metering program and loan program for both wind and solar, but the purchase prices are different across regions, which fluctuates based on the coal price. However, as this research would not consider the effectiveness of the incentive programs, all normalized incentives values for China are eventually 0 based on the function (11) in methodology and data collection selection.

Additionally, within each region, the ranking is given based on the difference in the normalized score. According to Table 4, the top three performers in western China and the western US are Inner Mongolia, Qinghai, Ningxia, Colorado, Arizona, and Wyoming, respectively. On the other hand, the bottom three performers in each region are Guangxi, Sichuan, Tibet and Idaho, Washington, and Utah.

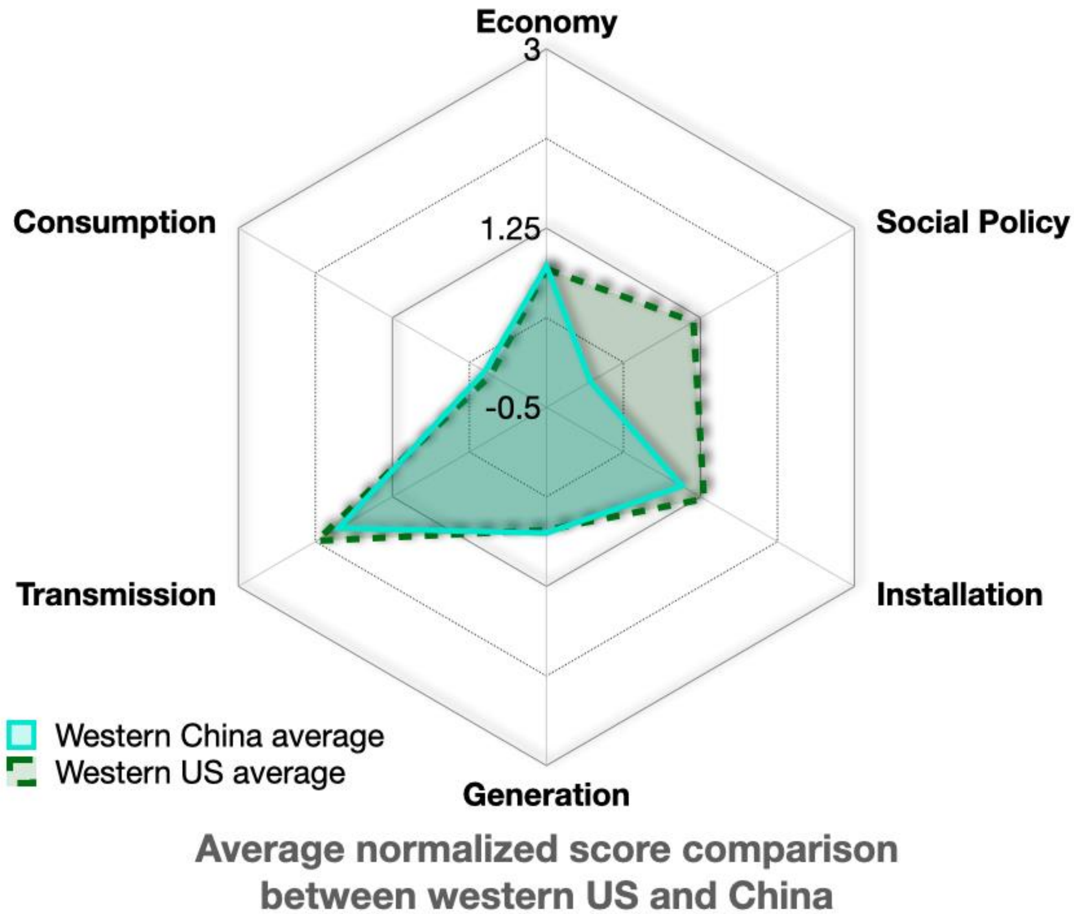


Figure 18 Average normalized result of western US and China

Fig.18: The light blue color represents the western China's average, the dark green color represents the western US's average. Without considering the development phases, western China performed as well as the western US in all factors except the social policy.

Table 4 Ranking and normalized score for the western US and western China

Province/States	Normalized Score	Ranking
Guangxi	3.86	10
Xinjiang	4.67	6
Tibet	2.71	12
Gansu	4.26	8
Shaanxi	5.17	4
Yunnan	4.11	9
Chongqing	4.81	5
Sichuan	3.75	11
Qinghai	6.48	2
Ningxia	5.83	3
Guizhou	4.34	7
Inner Mongolia	6.49	1
Western Average	4.71	-
Western STD	1.09	-
California	6.65	4
Washington	5.38	10
Oregon	6.33	5
Idaho	5.62	9
Montana	6.11	6
Nevada	5.91	8
New Mexico	5.96	7
Arizona	6.91	2
Utah	5.33	11
Colorado	7.88	1
Wyoming	6.66	3
Western Average	6.25	-
Western STD	0.72	-

Table 4: Table 4 above shows each province and state's final solar and wind development score in both western regions. The normalized score should only be used to compare within each western region, but the ranking order can compare horizontally.

4.2 Horizontal comparison

The final result can be used to conduct a horizontal comparison so that each province in western China can pair with states in the US, given their ranking result. The same ranking order indicates that a state or a province has relatively the same solar and wind development status compared with the others in a given region. For example, Inner Mongolia and Colorado are top ranked individuals in their region. Although they are not normalized within one group, the value of each factor is not able to compare directly. It is obvious to see that the most significant factor that Inner Mongolia currently needs to catch up on is social policy. In the future, Inner Mongolia should have a more diversified solar and wind incentives program to maintain its ranking within western China and keep paring with Colorado. Similarly, Colorado should improve its consumption factor in the future as well.

4.3 Vertical comparison

Horizontally comparing two entries in both regions can pair states and provinces based on their similar ranking. Also, it helps provinces and states find which factors both should improve in the future to maintain their regional development status. Last but not least, a vertical comparison is the third way to interpret the result, and it can further explain the reasons caused the performance difference within each region.

In western China, as the provincial level normalized performance data shown in Figure 19, unexpectedly, Qinghai led the performance in installation and generation. In contrast, Inner Mongolia, Yunnan, and Chongqing led correspondingly in the transmission, consumption, and economy. As Chongqing used to be the most vital economic power in western China, the electricity demand is high. It cannot produce electricity on its own, which causes the lowest value in the consumption category. Meanwhile, Chongqing also has the lowest normalized value in the generation category, which indicates the percentage of solar and wind it generated in 2020, which is the lowest compared with the rest of the provinces in western China. Given its limited land space and relatively poor solar and wind resources, it is reasonable that Chongqing finally ranks as 11 among 12 provinces.

Conversely, having limited land space but abundant solar and wind resources, Ningxia ranks third as it has a strong generation score. Located at the Qinghai-Tibet Plateau and has a limited population and electricity demand, the development of solar and wind in Tibet is the worst in the western region. On the other side, Qinghai has similar natural conditions as Tibet, but it ranks third, which benefits from its generation and installation performance mentioned above.

Inner Mongolia, Xinjiang, and Gansu have similar natural conditions. However, their results are quite different due to the influence of Gansu's poor economic performance and the unimpressive results of its consumption and installation, which Xinjiang is supposed to be strong. Social policy factor does not affect the ranking as all provinces share identical results.

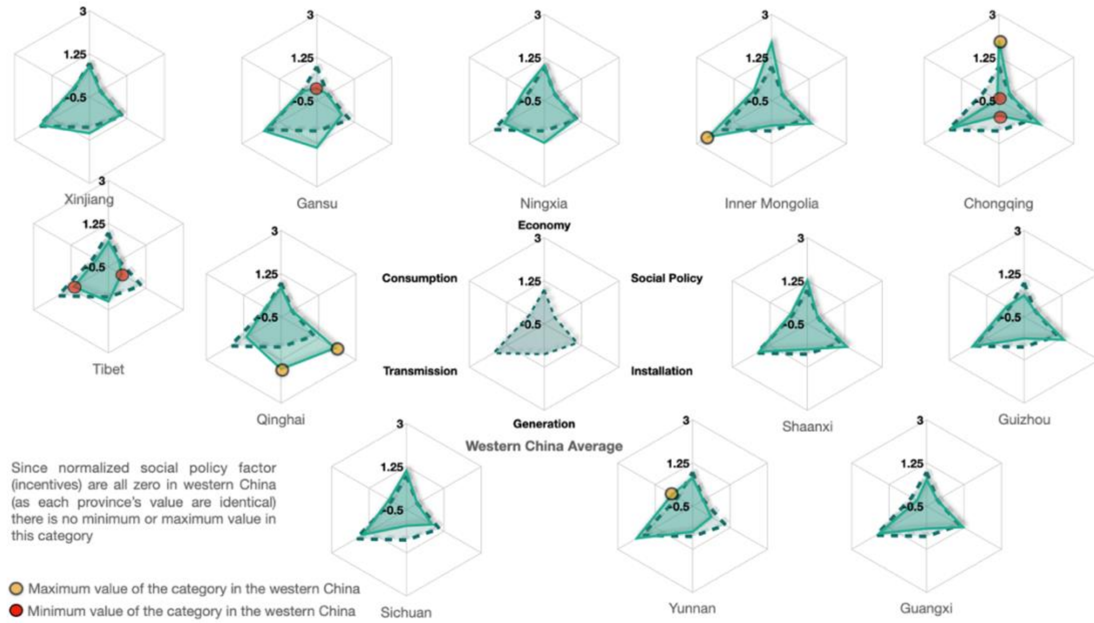


Figure 19 Normalized result of the provinces in western China

Fig.19: Yellow spot represents the highest value of the category, and red represents the minimum value of the category. Overall, Tibet and Chongqing have two lowest value, Qinghai has two highest value.

In the western US, Figure 20 shows that although each Arizona and California lead two factors, transmission, and social policy score and generation and installation, respectively, the first place was taken by Colorado unexpectedly. This is because Arizona scored the generation worst while California scored the best, and California scored the transmission worst, which is one of the most significant advantages of Arizona. The reason caused California's transmission score is meager because it imported the most outstanding amount of electricity from the other states. Although it imported a tremendous amount of electricity and is one of the most populated states in the western US and US, California’s consumption score is not the worst, but Idaho, which, thanks to its cumulative solar and wind installation in the past few years. In 2020, 23% of electricity in California was from solar and 7% from wind. Although Washington state has the most remarkable economic score, it offers its residents minor categories of wind and solar incentives. Utah ranks as the last, but all of its factors' performance is somehow even compared with the rest.

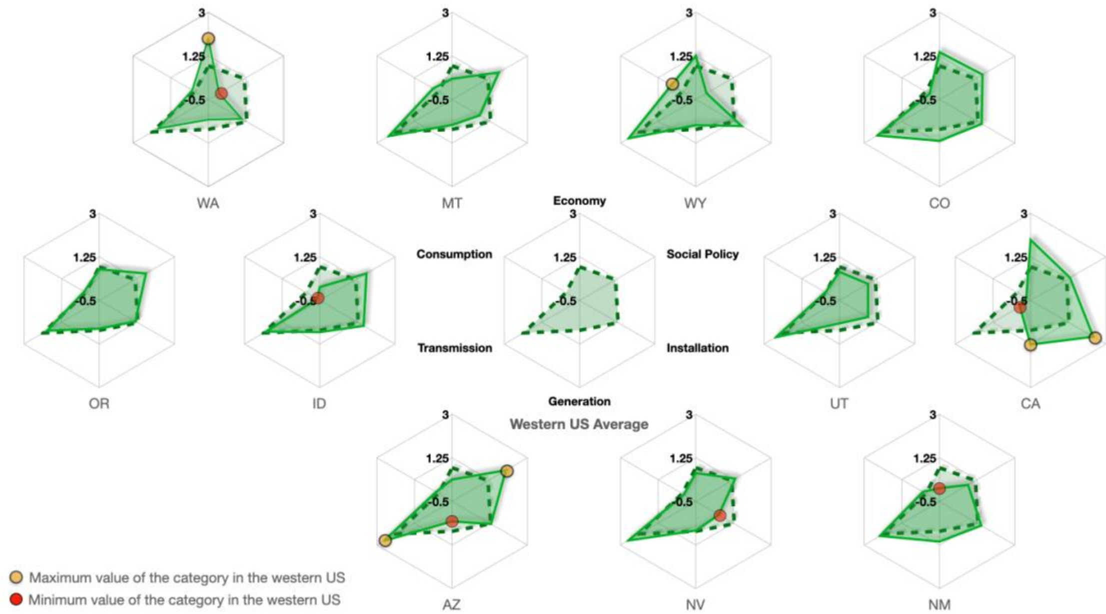


Figure 20 Normalized result of the states in the western US

Fig.20: California and Arizona have two highest value.

4.4 Discussion and limitation

The advantage of the designed framework is using the weighted average of the normalized value of different influential factors, regardless of their units, to conduct an assessment regarding a region's renewable energy development. It can also be used to assess one renewable energy, such as biomass in a region, or several renewable energy in a region combined if necessary. However, all vital influential factors need to be defined first. Different weights can be applied if any evidence demonstrates that one factor is more important than the rest, as long as the assumption is logical and reasonable. Although the weighted average method provides flexibility, the data accuracy would significantly affect the final result.

Starting from the outside factors, in this study, other sub-factors of selected outside factors may have a potential influence on the development of solar and wind energy in both countries, such as residents' education level, which may potentially influence their decision on if they would install a solar panel on the roof or not. Moreover, within the social policy category, whether the difference in the organizational structure and energy legislation process in both countries had an impact on the final result needs to be explored further in the future study. Regarding the incentives' category, some states also have a sales tax credit program. However, this study only selected the most commonly appeared incentives provided by the *Database of State Incentives for Renewables & Efficiency* (Database of State Incentives for Renewables & Efficiency®, 2022). Above information conclude the first limitation of the study. Given the widely existence of these sub-factors, for simplicity, it's reasonable for this study only select GDP per capita and disposable income per capita to conduct economic value and only use the most commonly appeared six incentives to be the sub-factors of the social policy factor.

The next limitation is the incentive types were categorized and designed by the US institution, not China. It may be biased to use a similar standard to evaluate provinces in China, as China only has a net metering program and loan program. The third limitation is only using the value 1 or 0 to represent the existence but not quantity further based on the effectiveness of the incentives. However, in real life, it's extremely difficult to quantify the effectiveness of each individual incentive in each province as the beneficiaries have various situation. For example, loan program. Given the nature of the loan program, which is assessed based on personal or company credit records, and the net metering allowance is fluctuated based on the coal price of each province, which is continually changing across years and regions, it is impossible to control those uncertainties across regions in both countries without bias. Thus, using China's incentives standard is impossible to conduct a consistent quantitative comparison. Although this study commit the existence of such limitation, it's the still optimal choice to use standard provided by Database of State Incentives for Renewables & Efficiency.

Similar as the first limitation mentioned above, the selection of sub-factors in inside factors also have limitation as well. According to the data collection section, there are five inside factors selected. Under the installation factor, there are two sub-factors: the 5-year average new installation ratio and the cumulative installed capacity of wind and solar. Although this research attempts to avoid timing bias, some people may argue that a 10-year or 20-year new installation ratio is more reasonable.

The next limitation exists in installation sub factors' selection. As one sub-factor is the cumulative installed capacity until 2020, it may also contain geological bias. Solar and cumulative wind installation in California is more than in Idaho or Oregon; this fact is thanks to California's massive demand due to the population advantage and the influence of its appropriate climate and area size. The key reason to select cumulative data is to demonstrate the historical efforts a state or province has put into the wind and solar energy development, even if they take advantage of its natural conditions.

Data missing for 5-year curtailment rate in provincial and state level is the next limitation. Solar and wind curtailment used to be a popular topic in grid connection and have been widely discussed in the literature. However, this study does not include the curtailment data for two reasons. First, public resources from NERL or EIA only conducted curtailment data based on ISO/RTO region. Most of California is categorized by CAISO, which can use the curtailment data of CAISO. However, states such as Montana have more than one ISO/RTO it is impossible to assign a curtailment value to that state. Second, curtailment data needs to use at least 5-year data to avoid timing bias, which adds additional difficulty to collecting both solar and wind data.

As a sub-factor of transmission loss in transmission factor, it is more reasonable to use the loss percentage over to its total generation of that year. However, since most of the grid is connected, it is hard to find out the amount of electricity lost in a state or province that was initially generated in this province. Thus, the loss percentage over to its total generation may also have a bias as a state may help the other take such adverse credit during the transmission process. It makes sense to use the amount of transmission loss solely. Export or import status may use a 5-year average as well; however, due to the limited availability of the data, this study only includes 2020's export and import data.

CHAPTER 5 POLICY IMPLICATION

5.1. Policy implication for China

5.1.1 Increasing distributed installation by implementing more social incentives

The results from the previous chapter indicate that all western provinces in China performed poorly in the incentives category as China lacks diversified incentives as the west US does.

Incentives such as personal or corporate tax credit programs could significantly increase the willingness of individuals or small businesses to use solar and wind, it's critical for both national and provincial governments to implement similar policies in the future. Provinces ranked at the bottom should pay more attention to it. Having property tax deduction incentive also encourage property owners to install the solar roof as the total cost of the installation is lower than the tax they saved from property transactions. However, the average normalized result in both western regions is similar in the economy, transmission, consumption, generation, and installation. Facts show that the development of solar and wind energy in China is more government-dominated, with a more centralized grid-connected PV power station. While in the western US, facts show that there are more distributed wind and solar capacities, which is probably caused by the combined effect between the difference of building types in both countries and social incentives. As most of the residential properties in China are apartment-style buildings instead of detached houses, it's not feasible for China to implement a property tax deduction program as there is not enough space on the roof (an apartment is sharing the same top) or beside building to build solar and wind infrastructures.

5.1.2 Building more industrial parks beside the solar and wind generating centres

Instead of transmitting all generated green electricity to eastern China, China should build more load centres besides the wind and solar farms, where they can consume the electricity directly through a microgrid. After burdening a significant amount of transmission loss in decades due to most major load centres located in the eastern area, while curtailment issues nagged newly installed distributed solar and wind capacity continually in western China, western provinces need to explore an innovative way to improve the overall efficiency.

Some view has mentioned that western China should boost the amount of green electricity transmission to generate revenue from the eastern area. However, it's infeasible. One of the CPPCC members, Neil Shen, proposed that the western provinces can sell green electricity to eastern provinces to trade economic growth in the future. He pointed out this view during the two sessions in 2022, which is the annual sessions of the National People's Congress (NPC) and the National Committee of the Chinese People's Political Consultative Conference (CPPCC). However, he also admitted that it was difficult at this stage as the grid connection is a significant problem due to the construction speed of the electricity grid needing to catch up (xinhua, 2021). It was extremely costly and challenging to construct an electricity grid across the country, from west to east. Two monopolistic companies, State Grid Corporation of China (SGCC) and China Southern Power Grid (CSPG), need more incentives to speed up the additional grids' construction for unconnected green electricity.

Moreover, cross-regional electricity transmission is not limited only by the physical constraints of the transmission system but also by the political and economic interests of the sending and receiving provinces. After the fiscal reform in 1994, national state-owned firms (SOEs) paid income tax directly to the central government, while provincial SOEs paid income tax to the provincial government. Due to most resource taxes (e.g., coal) going to the local government, provincial governments prefer to protect local power generators and profitable coal companies from generating local government revenue. Doing this ensures local employment rather than importing slightly cheaper green electricity to reduce local business costs. It is needless to consider importing green electricity when the price is higher unless the central government requires it. Especially during the post-covid era, when the national economy is slowing down, provinces consuming electricity are more reluctant to import electricity from outside (Ministry of Finance of People Republic of China, 2012).

Thus, given the situation above, western China should not seek to boost transmission amount but build more load centers, such as industrial parks and solar and wind farms. It's not feasible to build load centers such as a brand new city with millions of people in one or two days, nor attract half a million people to its current towns from the other provinces to increase demand quickly. Given the significant amount of industrial parks already located in the western regions, which take advantage of its low cost of land use or traditional energy's cost benefits, it would be optimal to let green electricity power those industrial parks. In recent years, Inner Mongolia has launched a “zero” emission industrial park and will introduce it below.

5.1.3 Introduction to Ordos “zero” emission industrial park

Sponsored by the Institute for Carbon Neutrality of Tsinghua University, a field trip to visit a “zero” emission industrial park located at the Ordos of Inner Mongolia was taken in October 2022. Ordos “zero” emission industrial park launched in the spring of 2021; Figure 21 was the photo of the park’s boundary taken during the field trip, and the park targeted to let 80% of electricity powered by solar and wind resources and 20% came from the grid in the future (chinanews, n.d.). Regarding the industry selection, the park strategically targets renewable manufacturers of mono-crystalline and multi-crystalline wafer manufacturers or wind panels. After interviewing with the industrial park management committee, the manager shared the future blueprint of the park, which is taking advantage of the abundant local solar and wind resources and the synergy of selected firms’ cooperation in the garden. Eventually, a sustainable energy cycle, as well as an economic process, can be developed at the same time. Solar companies can use their products to help the park install building-integrated photovoltaics (BIPV) for a sustainable energy cycle, given they have a significant amount of empty roof areas. Generated solar electricity can power the manufacturing process of other renewable energy infrastructures. The excessive amount of generated electricity can be either stored in a battery, which was the primary product of the other firm, or used to produce hydrogen. The produced hydrogen can also be stored in the hydrogen refuelling stations that power the hydrogen truck. All products’ transportation in the park will use hydrogen trucks in the future. Additionally, a hydrogen engine manufacturing firm in the garden can help this green transportation cycle even better.

Until now, Ordos' "zero" emission industrial park was the first “zero” industrial park in the world. Although it has yet to determine if the garden can meet the expectation in the future, it is a great attempt and an innovative way to optimize solar and wind electricity use in western China and boost the local economy.

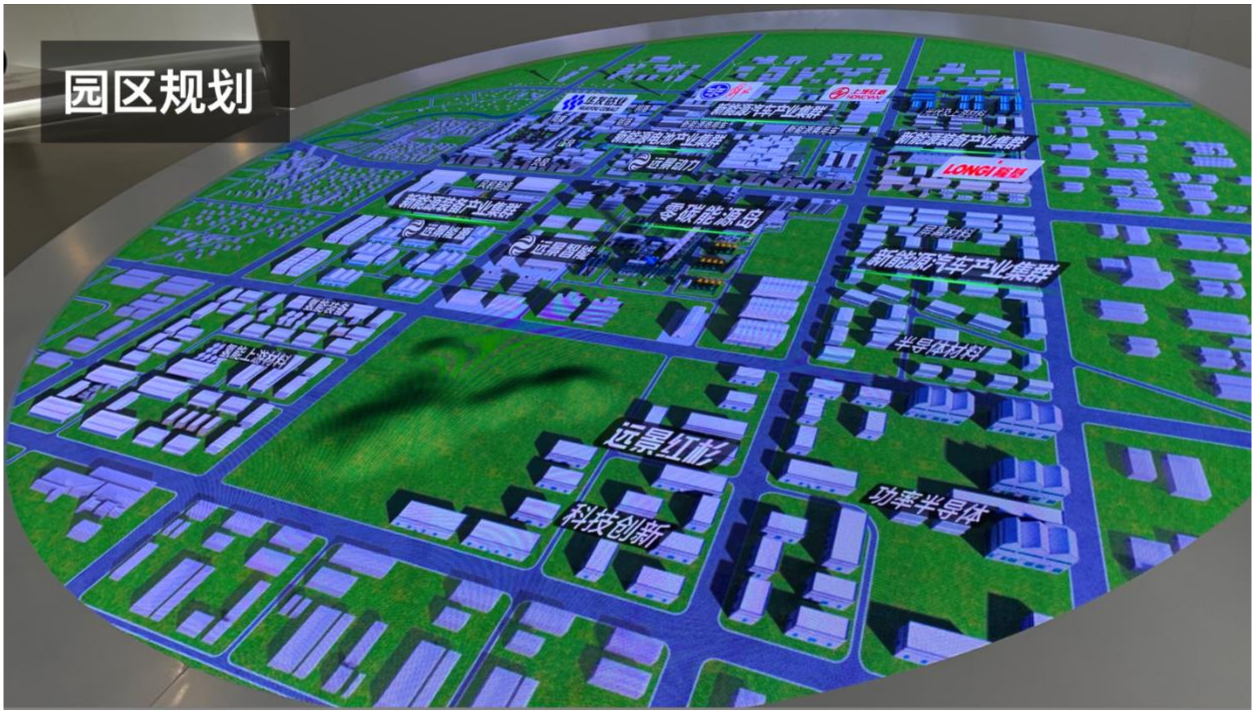


Figure 21 Map of Ordos "zero" emission industrial park

Fig.21: This picture is taken by Haoge Xu at Envision Group, Ordors.

5.2 Policy implication for the US

5.2.1 Upgrading electric grid system and replacing aged facilities

Without considering the development phase difference, the result shows that western US development status was close to western China except for the social policy factor. The advantage of the US grid system is that it has several grid systems. The two countries' grid systems differences are demonstrated in Figure 22. In the US, three "Interconnections" appeared in Figure 23, representing the transmission region in the US primarily independent with minimal power exchange. There are 66 "Balancing Authorities" balance supply and demand for their administrative area and ensure Federal reliability standards are met (U.S. Electricity System, n.d.). Compared with China's grid system, which needs to transmit electricity far from the west to the east, the proximity allows the US to have less transmission loss and makes it easier to develop a regional strategy. However, in recent years more and more evidence shows that the increasing transmission loss was caused by the old grid system. Thus, the western US must upgrade its aged facilities on time to maintain the transmission advantage.

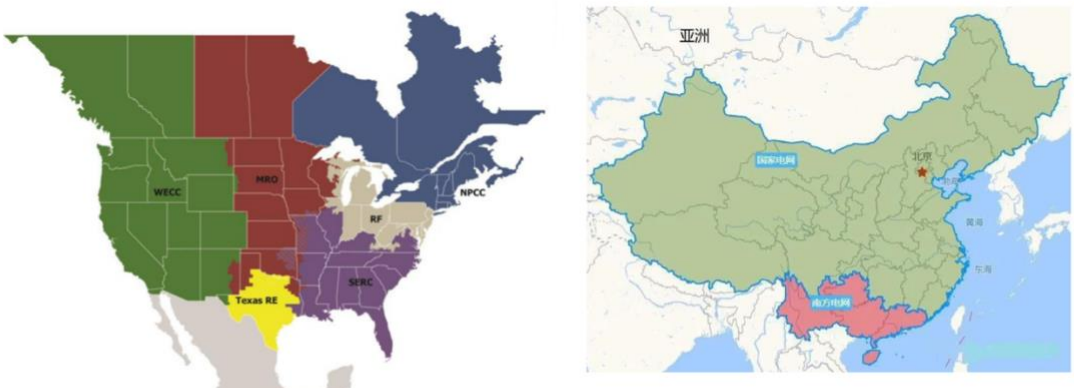
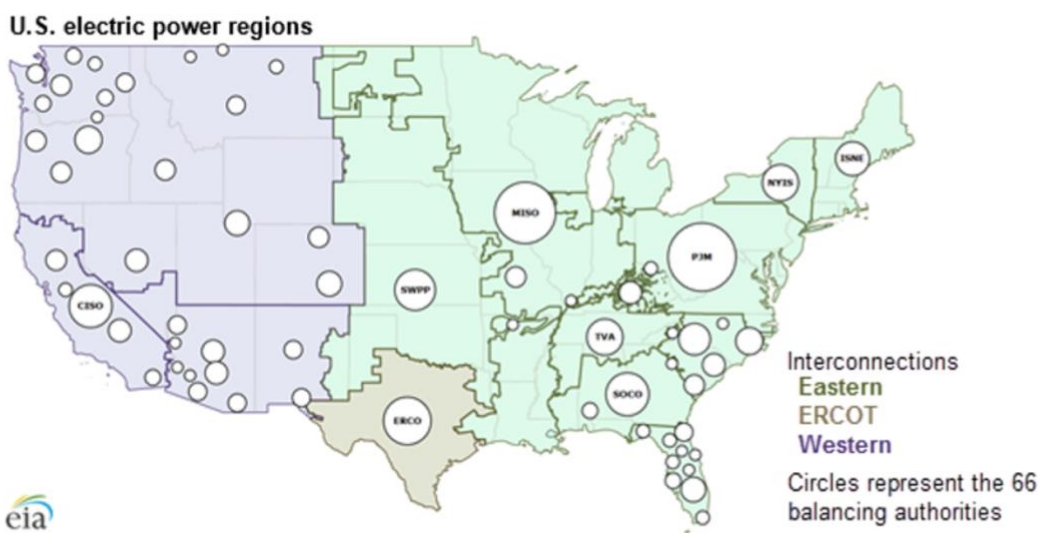


Figure 22 Electric system comparison between the US and China

Fig.22: The difference of electric system in China and the US. The US has six regions, while China only has two regions.



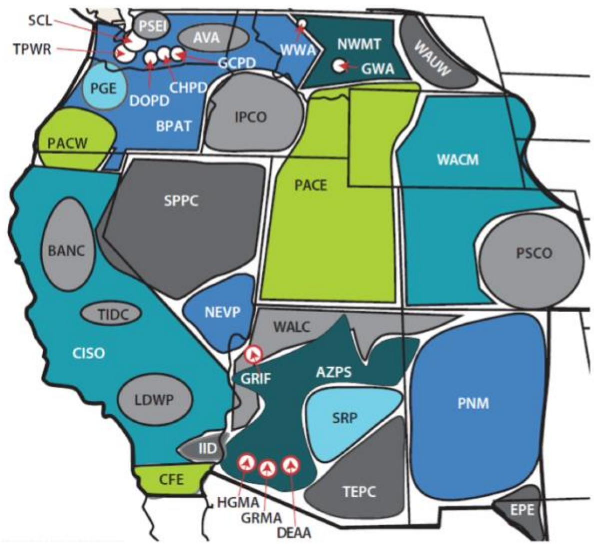


Figure 23 Electric system and balancing authorities in the US

Fig.23: The are several balancing in the western US, and the electric system boundary doesn't follow the state boundary. California has five electric systems.

CHAPTER 6 CONCLUSION

This paper designed an evaluative framework to measure solar and wind energy development in the western US and western China in 2020 based on the normalized value of 6 selected factors. Each factor is selected based on the critical process of solar and wind electricity generation; moreover, the normalized value of each factor is composed of the normalized value of selected sub-factors. Selected sub-factors can vary. However, given the limited data existence and the difference in statistical standards in both countries, 24 types of sub-factors in each country have been selected to conduct this assessment.

Unexpected results show that, in 2020, the top three solar and wind performers in the western US are Colorado, Arizona, and Wyoming. Furthermore, they are Inner Mongolia, Qinghai, and Ningxia in western China. The conducted results can be used to make the comparison in three ways.

By comparing the average value of the normalized score of the two regions, this study found that the average normalized score in each factor between the two western regions is very close, except for the social policy perspective. Specifically, it indicates that, without considering the development bias between the two regions, western China, at the current stage, performed as well as the western US, except for the availability of solar and wind incentives.

By comparing the result horizontally, without comparing the final normalized score between the western US and western China as they are not normalized in the same scale, but solely comparing their ranking order number, provinces in China can pair with states in the western US with the same ranking order. If their US partners have an advanced experience that can be learned from them, in the future, provinces in China can keep tracking those states to take lessons from them regarding solar and wind development.

Vertically comparison tells that each province and state will receive a ranking order within its region by comparing the result vertically. These provinces can compare their performance in each factor among their western peers to conduct a strategic plan in the future.

Based on the results, this study concludes two policy implications for western China and one for the western US. First, western China should implement more social incentives to encourage residents and commercial users to install solar and wind generators. Second, instead of waiting for new electricity grid construction, western China should build more loads center to reduce transmission loss and save construction costs, a crucial lesson taken from the western US. However, load centers in the western US are majorly big cities. Western China should build more industrial parks, given its abundant land, fossil fuel resources, and existing industrial foundation, besides the solar and wind generating centers. Ordos' "zero" emission park will be an excellent example for the rest of the western provinces to study if it can demonstrate its success in the future. As transmission loss increases, one lesson the western US could take is upgrading the electric grid system and replacing aged facilities.

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