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Sustainable Energy Transitions in China: Renewable Options and Impacts on the Electricity System

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Abstract: Chinese energy consumption has been dominated by coal for decades, but this needs to change to protect the environment and mitigate anthropogenic climate change. Renewable energy development is needed to fulfil the Intended Nationally Determined Contribution (INDC) for the post-2020 period, as stated on the 2015 United Nations Climate Change Conference in Paris. This paper reviews the potential of renewable energy in China and how it could be utilised to meet the INDC goals. A business-as-usual case and eight alternative scenarios with 40% renewable electricity are explored using the EnergyPLAN model to visualise out to the year 2030. Five criteria (total cost, total capacity, excess electricity, CO_2 emissions, and direct job creation) are used to assess the sustainability of the scenarios. The results indicate that renewables can meet the goal of a 20% share of non-fossil energy in primary energy and 40%–50% share of non-fossil energy in electricity power. The low nuclear-hydro power scenario is the most optimal scenario based on the used evaluation criteria. The Chinese government should implement new policies aimed at promoting integrated development of wind power and solar PV.

Keywords: EnergyPLAN; energy transition; renewable energy mix; sustainability assessment

1. Introduction

Renewable energy development is an important measure to address the issues of climate change and energy security [1]. Both developed and developing countries have committed to reducing their greenhouse gas emissions through increased use of renewable energy (RE) [2]. China formally submitted its Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change for the post-2020 period. In this climate change mitigation plan, five objectives are to be realized by 2030: (i) achieving a peak in carbon emissions by 2030 or earlier; (ii) increasing the share of non-fossil fuels in primary energy consumption to account for at least 20%; (iii) lowering carbon dioxide emissions per unit of Gross Domestic Product (GDP) by 60%–65% from 2005 levels around 2030; (iv) increasing its forest stock volume by 4.5 billion cubic meters (increase of 32.8%) compared to 2005 levels; (v) putting forward regulatory measures to limit or reduce greenhouse gas (GHG) emissions [3].

Currently, thermal power plants, especially coal-fired plants, account for the majority of all electricity generation in China. In 2012, China had 669,259 megawatt (MW) of installed capacity in 2929 coal-fired power plants that accounted for 71.48% of China's total installed capacity and produced

78.72% of its total electricity output [4,5]. New installations of non-fossil electricity generation capacity should be 800–1000 gigawatt (GW) in the next 15 years to meet the INDC targets [6].

After the release of INDC, institutions increased their forecast on the non-fossil energy share in total primary energy consumption. Compared with earlier projections, several institutions increased their expected share of non-fossil primary energy consumption after the INDC was submitted. A Massachusetts Institute of Technology (MIT) study foresaw that the percentage of non-fossil energy consumption will be 14.4% in 2030 [7], but increased this to 24.3% in their latest report [8]. In the International Energy Agency (IEA)'s *New Policies Scenario* a 21.1% share of non-fossil fuels in primary energy demand by 2030 is indicated [9], which is an increase of 6% compared with the preceding 2014 report (15.16% of non-fossil energy in total primary energy supply (TPES)) [10]. ExxonMobil did not present projections for 2030, but non-fossil energy share increased from 15% to 23% between 2025 and 2040 [11]. Though the renewable energy target is clear, there was no specific pathways for the government to achieve the goal.

1.1. Literature Reviews

The definition of "*sustainable energy*" was first presented in the United Nations World Commission on Environment and Development (UN WCED) report as "*a safe, environmentally sound, and economically viable energy pathway that will sustain human progress into the distant future is clearly imperative*" [12]. This is the basis for subsequent research aimed at quantifying the sustainability of energy systems on various dimensions, such as economic, environmental, social, and technical factors [13]. Three core energy transition pathways were set by Reference [14]—"Market Rules, Central Co-ordination and Thousand Flowers". Reference [14] summarised the key technological and institutional changes in these pathways. Top-down and bottom-up models such as Long-range Energy Alternatives Planning system (LEAP) [15], Integrated MARKAL-EFOM System (TIMES) [16] are frequently applied to analysis the energy transition pathway in electricity sector. However, results from ex-post models that focus on cost optimization does not approximate the real world UK electricity system transition in 1990–2014 by reviewing the rationale for the use of cost optimization [17]. By using an Excel-based "Energy Optimisation Calculator", reference [18] develop a policy-informed optimal electricity generation scenario to assess the sector's transition to 2050, analysing the level of deployment of electricity generating technologies in line with the 80% by 2050 emission target. Reference [19] presents a multi-objective optimization model for a long-term generation mix in Indonesia to assess the economic, environment, and adequacy of local energy sources. Reference [20] compared generation portfolios on the basis of expected costs, cost risk and greenhouse gas emissions, with a view to understanding the merits and disadvantages of gas and renewable technologies by applying a Monte-Carlo based generation portfolio modelling tool. Reference [21] established newly developed multi-level perspective (MLP) transitions with three lines of thought and five transition pathways to study the transition to low carbon power systems in China. Reference [22] studied energy transition at the regional level in rural China by presenting an improved graphical pinch analysis-based approach considering carbon-constrained regional electricity planning and supply chain synthesis of biomass. Reference [23] presents the results of the German Energy Reference Forecast by using an investment and dispatch model for the European electricity sector emphasis on the time period up to 2030. These models cannot take the non-controllable generation characteristics into consideration. A methodology which can model the electricity supply mix that meets the hourly electricity demand is required. What is more, total system costs could not be the only optimization objective, as energy transition is not dominated by lowering the total system costs.

1.2. Scope and Structure of This Study

This study will investigate the sustainable pathways in the power sector to realise the 20% share of renewable energy in primary energy consumption used for power generation. Energy transition pathways are printed as generation mix and are simulated by hourly total supply scenarios to meet hourly demand. The sustainability of each pathway is evaluated with five factors from economic, social-economic, environmental and technical dimensionalities. Firstly, the paper reviewed the potential of main renewable energy for electricity generation, possible renewable power installed capacity and energy policy that promote the evolution of renewable generation and consumption from existing governmental and academic researches. This information decides the installed capacities that can be assumed in the transition pathways. Secondly, EnergyPLAN model or software and multi-criteria analysis are introduced in Section 3. In this section, five criteria are considered, namely: (i) total costs (ii) total installed capacity (iii) excess electricity; (iv) CO_2 emissions; and (v) direct job creation. Four of the parameters were quantified for different energy scenarios using the EnergyPLAN model, which is capable of using hour-by-hour resolution to capture the production dynamics in a system with a high share of renewable electricity generation. In contrast, direct job creation was quantified using an employment factor approach. In Section 4, nine electricity generation mix scenarios that driven by different renewable energies are established. In Section 5, EnergyPLAN model introduced in Section 3 are applied with the nine generation scenarios with the data provided in Section 4. Then the sustainability of different scenarios is compared with the multi-criteria analysis mentioned in Section 3. This study presented a methodology to evaluate the energy transition in power sector and will provide more reliable energy transition pathways choices for the decision-makers from a system perspective.

2. Electricity System and Policy of China

Thermal coal-fired power still account for more than 70% in total electricity production in China, despite significant progress in development and installation of renewable energy technologies [24]. One important factor to consider in understanding the differences and potential of alternative energy technologies is the capacity factor, as this can lead to significant incongruities between installed capacity and real generation [25].

The capacity factor is the ratio of actual output over a period of time, to its potential output if it were possible for it to operate at full capacity continuously over the same period of time. This is typically calculated using annual data. For example, Chinese wind power produced 153.4 terawatt hours (TWh) of electricity from a total installed wind capacity of 114,599 MW in 2014 [26]. The average capacity factor of wind power in China was 22.4% for 2012, 23.7% for 2013, and 21.6% for 2014 [26]. In contrast, corresponding capacity factors are 58% for overall across all fossil fuels power and 34% for hydropower according to the IEA [27]. In summary, a thermal power plant can produce roughly twice the electricity output of a wind farm with the same installed capacity. Importantly, it is recognised that wind and solar electricity in particular have non-controllable generation characteristics, with the capacity factor largely attributable to natural conditions at the site of installation. On the other hand, conventional fossil fuel technologies can operate to provide planned output, so the capacity factor is largely controllable (apart from maintenance and unexpected outages). Economics of current technologies typically drive the capacity factors of inexpensive generators (coal and nuclear) to be higher—often greater than 80%—with peak, middle and load balancing technologies (oil and natural gas) having lower capacity factors (~40%). Hydropower is a largely controllable power source, but seasonal differences in water inflow may impact on the ability to generate at full-load.

Capacity factors can reflect the overall utilization of installed capacity and its importance for energy production, but it cannot fully capture changes in electricity generation on shorter time frames. It is important to study changes in electric output over a daily or even hourly basis due to the intermittent nature of many renewable energy technologies.

2.1. Potential of RES for Electricity Production

China has abundant potential for hydro, wind, solar, biomass, and other renewable energy sources [28]. In recent years, specific policies were introduced to support large-scale development of RE, such as a mandatory market share for renewables by sector and technology, feed-in-tariff-based support mechanisms, and government financial support for renewable energy projects [29]. Total renewable electricity production increased from 825.49 TWh/y in 2010 to 1486.45 TWh/y in 2014 [30].

2.1.1. Hydropower

One widely used estimate of the national potential of hydropower electricity was derived from the 4th national survey of hydro resources in 2005 [28]. It estimated the gross theoretical hydropower potential of 6.08 million GWh/y with an average capacity of 694 GW; technically exploitable hydropower was considered to be 2.47 million GWh/y with an installed capacity of 542 GW; economically exploitable hydropower was 1.75 million GWh/y with an installed capacity of 402 GW [28], of which small hydro power plants with an installed capacity below 50 MW account for 128 GW [31,32]. China commissioned almost 22 GW of hydropower dams for a year-end total of 280 GW in 2014 [33]. The resulting electricity generation from hydropower increased to 144.05 TWh and this corresponded to an increase of 15.65% [30] while the economic potential remaining would therefore be assumed to be around 120 GW.

2.1.2. Wind Power

In 2014, China added about 23.2 GW of new wind turbines—more than any country has ever installed in a single year—for a total installed capacity approaching 115 GW [34]. About 20.7 GW was integrated into the national grid and started receiving feed-in tariff premiums during 2014, with cumulative historical installations of approximately 95.8 GW officially considered grid-connected by that year's end [35]. Wind generated 156.3 TWh in 2014 and accounted for 2.8% of total electricity generation in China (a marginal increase from 2.6% in 2013) [36].

Table 1. Wind power potential.

Measurement Agency (Year)	Available Areas (Thousand km^2)	Height (m)	Technical Exploitable Resources (GW)	References
Onshore				
The 2nd Survey on National Wind Power Resources (1990s)		10	253	[31,36–38]
China Meteorological Administration (2007)	200	10	297	[38,39]
China Meteorological Administration (2007)	540	50	2680	[38]
United Nations Environment Programme (2004)	284	50	1420	[40]
China Meteorological Administration (2009)		50	2380	[32,41]
China Meteorological Administration (2011)		50 70 100	2000 2600 3400	[42] [42] [32]
National Climate Centre (2006)		10	2548	[28]
China Meteorology Research Institute (2009)		10	1000	[43]
China National Renewable Energy Centre (2012)		>50	1300–2600	[41]
Chinese Academy of Engineering (2009)			300–1400	[44]
China Academy of Engineering (2008)			700–1200 [1]	[45]
US National Renewable Energy Laboratory (2003)		50	1400	[46]
Average onshore		10	1024.5	
		50	1976	

Table 1. *Cont.*

Measurement Agency (Year)	Available Areas (Thousand km²)	Height (m)	Technical Exploitable Resources (GW)	References
Offshore				
China Meteorological Administration (1990s)		10	750	[38,47]
United Nations Environment Programme (2004)	122	50	600	[31]
Chinese Academy of Sciences (2006)		10	2000	[38]
China Meteorological Administration (2007)	37	50	180	[38]
National Climate Centre (2009)		50	758	[38]
Energy Research Institute (2007)	30		150	[38]
China Meteorological Administration (2009)		50	200	[38]
Chinese Academy of Meteorological Science (2003)		10	3200	[40]
US National Renewable Energy Laboratory (2003)			600	[46]
China National Renewable Energy Centre (2012)		5–25	200	[41]
Average offshore		10	1983	
		50	434.5	

[1] Total economically exploitable resources.

Wind resources are abundant in China with promising onshore and offshore sites on its vast territory and along its coastlines [34]. Onshore wind resources account for 89% of total wind power potential in China based on assessments made in [36]. Existing estimations of wind power potential from government and institutions are normally estimated at heights of 10 or 50 m (see Table 1). Estimated average technical exploitable capacity of wind power are 1024.5 GW at 10 m height and 2120 GW at 50 m height. There is no explicit description of how much of this could be considered economically exploitable [43].

2.1.3. Solar Power

Annual solar radiation in China ranges from 1000 kWh/(m^2·day) to over 2000 kWh/(m^2·day) [28]. China is one of the countries with the highest solar potential and it has been estimated at 6900–70,100 TWh per year with a potential stationary solar capacity from 4700 GW to 39,300 GW and 200 GW of distributed solar capacity [48].

Two forms of solar resources are usable for large-scale exploitation, specifically deserts (including the Gobi and other desert-like regions) and building roofs. There were 1.08 million·km^2 of desert and 0.02 million·km^2 of building roofs after the end of the 11th five-year plan that could be used for solar generation [28]. China increased its cumulative installed capacity by 60%, adding 10.6 GW and generated about 25 billion kWh of electricity from solar PV in 2014, an increase of more than 200% over 2013 [34]. Over 80% of China's new capacity installations were as large-scale power plants, and the remainder were distributed roof-top systems and other small-scale applications [46]. The estimates of total potential are shown in Table 2.

Table 2. Solar PV power potential capacity and generation.

References	Capacity (GW)	Generation (TWh/y)	Assumed Capacity Factor	Description
[28]	n.a [1]	6480 + 1296	n.a [1]	Unclear
[42]	2200 + 500	n.a [1]	17% for Utility-scale projects, and about 15% for rooftop solar	Technical capacity, 2200 GW for utility and 500 for rooftop
[43]	n.a [1]	1300–6500	n.a [1]	Unclear
[45]	2200	n.a [1]	n.a [1]	Economic capacity
[49]	6486 [2] 9064 [2] 9114 [2]	51,133 71,461 71,858	90% 90% 90%	Technical potential Technical potential Technical potential
[48]	4700–39,300 200	6900–70,100	10.94%–23.79%	Stationary solar theoretical potential Distributed solar theoretical potential

[1] n.a: not available. [2] Unit: GW coal-eq. The coal capacity equivalent is the total coal power plant capacity required to generate an equivalent amount of electricity, assuming a capacity factor of 90% [49].

2.1.4. Other Renewable Sources

The Chinese bioenergy industry grew vigorously in size after the Renewable Energy Law came into effect in 2006 [50]. The installed capacity from biomass generation was 9.5 GW in 2014, 11% higher than that in 2013. However, there are no published assessments for the potential of biomass-fired power generation for China within existing literature.

Geothermal potential is vast with available resources estimated to 4885 TWh per annum according to the Ministry of Land and Resources [51]. Past decades saw a steady growth of geothermal generation. But up to 2014, the installed capacity from geothermal was just 27.28 GW and the potential remain largely untapped [51].

China has abundant ocean energy based on its long coastline. Ocean energy that can be used for generation is mainly tidal energy, wave energy, and ocean thermal energy, although the latter of these is not well-developed [52]. During the past decades, China invested considerable research efforts into these energy sources. It was estimated that the technically exploitable capacity that could use available ocean energy is around 20 GW. However, only tidal energy was mature enough for commercial development [28].

2.2. Electricity Demand and Supply

Approximately a third of China's total installed generation capacity (1.36 TW) consists of power plants using non-fossil energy, but only 24.4% of the total electricity demand was produced from non-fossil energy resources in 2014 [30,53]. Many Chinese and international studies still project rapid growth of electricity demand. Published projections range from 6254 to 11,900 TWh for 2030, with an average of 9790 TWh (Table 3). A variety of factors should be considered in these estimations, including assumed GDP growth, historical trends, the changing relative costs of various electricity generation technologies and the potential shift in China's industrial structure.

Table 3. Recent projections of electricity demand (TWh).

Study	2020	2030	2050
[9]	6254	8123	n.a [1]
[54]	8600	11,900	n.a [1]
[55]	n.a [1]	9900	14,300
[42]	n.a [1]	9543	n.a [1]
[56]	n.a [1]	n.a [1]	9100
[57]	6975	9483	n.a [1]
Average	7276	9790	11,700

[1] n.a: not available.

2.3. Energy Policy for the Future Electricity System

Reduction of smog and air pollution (caused by coal-fired power to a significant extent) has become a key public policy focus in China [58]. In recent years, the Chinese government issued several new energy strategies with distinct focus on environmental protection, energy security, energy efficiency, energy diversification, and socioeconomic development. These include China's Energy Policy 2012 [59], Action plan for energy development strategy (2014–2020) [60], Air Pollution Prevention and Control Action Plan (2013–2017) [61], and the 13th Five Year-Plan [62]. The key policy considerations are briefly presented as follows:

2.3.1. Protection of the Environment

China emitted a total of 9023.1 Mt CO_2 and accounted for 28% of world emissions in 2013, thus corresponding to the largest global source of emissions. Heat and power production accounted for 4416.9 Mt CO_2 [63], or roughly half of China's emissions. The submitted INDC indicates that Chinese CO_2 emissions should peak by 2030 [3]. Thus, the Chinese electricity sector must become a driving force for paving the road towards the low carbon energy system proposed in the INDC.

2.3.2. Increasing Energy Security

Access to reliable and affordable energy is one of the most important aspects of modern developed economies. Diversification of imported energy and increased use of domestic energy sources are two energy policy drivers aimed at improving Chinese energy security [58]. Electricity as a secondary energy carrier is flexible and could be generated from fossil, nuclear, or renewable energy sources. Electricity portfolio diversification allows China to enhance supply security despite increasing import dependence of some energy resources [64].

2.3.3. Improving Energy Efficiency

Improving energy efficiency is critical to achieving China's carbon intensity targets and energy efficiency and conservation are officially China's top energy priority. In 2008, China passed the Energy Conservation Law to boost energy efficiency throughout the Chinese economy [65]. In 2010, the NDRC implemented demand side management regulations that require utilities to achieve electricity savings of 0.3 percent per year, and reduce peak demand by the same percentage [66]. Unsmooth deployment of renewable energy that challenges the decarbonizing China's electricity system is a challenge that energy conservation and carbon mitigation will face [67]. Due to the characteristics of China's energy resource properties, the current power generation is given priority to coal mixture and produced huge emissions; this is the key problems of energy conservation and emissions reduction [57]. In China's Energy Development Strategy Action Plan (2014–2020), the share of coal consumption in the energy mix is capped to 62% [68].

3. Methodology

Energy system models are used to provide insight into future energy supply options. For long-term models, it is common that time resolution is simplified and energy production/consumption is often tracked by annual flows. This works well for fossil fuels and most established energy technologies, which are typically characterized by high capacity factors. However, the intermittent nature of many renewable energy sources and their electricity production characteristics require better time resolution to capture the dynamics in an electricity system with a significant share of RE [69,70]. Among the energy system models used for such systems, EnergyPLAN [71], Mesap PlaNet [72], H2RES [73], and SimREN [74] use time-steps of 1 h or less.

Model projections can be used for quantitative policy evaluation, provided that the model incorporates the desired factors. For example, costs are currently not considered in H2RES. In comparison, the EnergyPLAN model has several options and the majority employ a small range of model criteria such as primary energy supply, greenhouse emissions, excess power generation, business costs, export and/or import of electricity, etc. [75]. It is for this reason that EnergyPLAN was selected for use in this study.

3.1. EnergyPLAN

The EnergyPLAN model is a descriptive analytical model for medium/large-scale energy systems using multi-objective evolutionary algorithms to optimize solutions in the context of complex problems [76]. It can be employed to simulate and optimize energy systems with high shares of renewable energy on regional or national scales. The main mechanism of this model is balancing hourly electricity, heating, and other demand against production. Input data includes electricity, heating, cooling, and other consumption demands, capacity of electricity and heating plants, capacity of renewable power and its distribution.

Both technical and economic optimization strategies can be provided from the EnergyPLAN software. For technical optimization, the aim is to minimize fossil-fuel consumption without any cost considerations. For economic optimization the minimization is applied to total operational expenses [76,77].

The EnergyPLAN model cannot meet requirements for full sustainability and holistic environmental evaluations [78]. As of September 2015, EnergyPLAN had been used in 95 analyses in close to 50 scientific articles according to a recent review [75]. Most applications were on the country or state level to explore high shares of renewables in the energy system. Only a handful of these articles addressed the modelling methodology or inclusion of other technologies into the energy system (for more information see Figure A1 in the Appendix A).

3.2. Multi-Criteria Evaluation

Multi-criteria methods are widely used to assess sustainability in energy strategies and electricity mixes due to their ability to capture the complexity of socioeconomic and biophysical systems [79,80]. Multi-criteria assessments are useful for complex issues with significant uncertainty, different perspectives, various data forms, and diverse stakeholder opinions [81]. In this study, a multi-criteria analysis is used to evaluate the sustainability and impacts of different electricity generation mix scenarios using five different criteria: (i) total costs (ii) total installed capacity (iii) excess electricity; (iv) CO_2 emissions; and (v) direct job creation. The first four criteria can be directly obtained from the EnergyPLAN model and the fifth can be calculated separately.

Total installed capacity and excess electricity are two new factors compared with the others. This paper chose them as impacts on energy system according to [82,83]. Minimum total mix capacity method was developed by [79] as a means to identify the optimal renewable energy mix when fossil/nuclear electricity share is limited or when there is a minimum share of renewable power required in the electivity sector. That is minimum total mix capacity seeks to identify the optimal combination of energy mix when a minimum production of RES is specified [83]. Excess electricity production represents a serious problem for a system and must be avoid or the problem could face overcharging problems [82]. The intermittency of wind and solar power can result in temporary overproduction of electricity as more and more capacity is installed within the system. Minimization of excess energy is a crucial component of future RE systems [83], and the amount of electricity exceeding the existing demand could be used to assess electricity systems with high RE shares. The potential of pumped storage hydroelectricity as an electricity storage technology can be one way of mitigating this except for its high investment costs [83].

The fifth criteria is job creation to capture the socioeconomic impact of a transition towards a system with a large share of RE. The employment factor method has been used in many earlier studies [13,84,85] to assess employment from power plants. Job creation was calculated by different categories (by construction/installation, manufacturing and operations & maintenance [84] or as direct and indirect jobs [83,84]. Indirect jobs are created when money is spent to produce goods and services for building and operating and refer to subsequent flow-on job creation resulting from changing inputs required [86]. In this paper, only direct job creation is considered and employment factors are utilised from earlier work [86].

4. RE Scenarios and Assumptions

A set of nine scenarios for China's electricity generation mix in 2030 were created, including a Business-As-Usual (BAU) scenario and eight possible alternatives The base year is set to 2015 and different electricity systems are projected to 2030 using EnergyPLAN. Renewable energy, solar PV and wind power generation especially is intermittent depending on the weather or climate. Reference [48] compared the annual capacity factors of solar PV by province during 2001–2010. It shows that the capacity factors were relatively stable year by year, while the most challenging thing is the differences of capacity hour by hour, so this study chooses a topical hourly distribution of capacity factor from [87] and controlled it by the EnergyPLAN method. This paper models the power system by balancing hourly electricity demand with hourly electricity supply from different generation mixes considering the intermittent nature of renewable energy. Hourly electricity consumption curve, heating demand curve and hourly available distribution of renewable energy were provided from [87].

4.1. BAU Scenario

In the BAU scenario, this paper assumes that the generation mix in 2030 is the same as in [42]. Expected electricity demand for 2030 is based on the projections made by others [57] and the projected electricity supply by source in 2015 (heat and power (CHP): 21.19%, thermal: 49.45%, natural gas: 2.83%, nuclear: 3.49%, hydro: 17.89%, wind: 3.36%, solar photovoltaics (PV): 0.86%, CSP: 0.07% and biomass: 0.85%). All costs are adopted from the same source [87] except for concentrated solar power (CSP) which was taken from elsewhere [88] (see Table 4). Furthermore, pumped storage electricity production was not included as a significant balancing factor in the electricity system.

Table 4. Assumed annual costs for different technologies [89,90].

Prod. Type	Investment (Million RMB Per MW)	Life Time (Years)	Operation and Management (% of Investment)
Small CHP units	4	35	4
Large CHP units	4.2	30	4
Large power plants	4	40	3
Nuclear	13	60	3
Wind	4	20	2
PV	7.5	20	0.5
Hydro power	5	50	0.5
CSP solar power	31.62	25	1

4.2. Alternative Scenarios for an RE-40 System

The Chinese government does not specify detailed numbers for the share of specific RE technologies in their plan. The aim is to increase the rate of zero-emissions generation from about 30% to 40%–50% (46%, according to the Bloomberg New Energy Finance outlook by 2030 and the ambition depends on growth of the economy as a whole [89]. Based on this target and its INDC 20% renewable share in total primary energy consumption target, this paper assumes that renewables (hydropower, wind power, solar PV power and biomass) account for 40% of total generation by 2030 (see in Table 5).

Table 5. Scenario details and names used in this study.

Alternative Scenarios	Description	Assumed Installed Capacity (GW)			
		Nuclear	Hydro	Wind	Solar PV
LN-H	Low nuclear-high Hydro	120	585	400	331
HN-W	Low nuclear-high Wind	120	400	800	112
LN-PV	Low nuclear-high PV	120	400	341	800
LN-B	Low nuclear-Balanced mix	120	440	500	480
HN-H	High nuclear-high Hydro	200	585	400	331
HN-W	High nuclear-high Wind	200	400	800	112
HN-PV	High nuclear-high PV	200	400	341	800
HN-B	High nuclear-Balanced mix	200	440	500	480

This paper establishes eight alternative scenarios based on the RE potential in China, all with the common characteristic of 40% RE but generated by different mixtures of RE technologies. These are: (1) low nuclear-hydropower; (2) low nuclear-wind power; (3) low nuclear-PV; (4) balanced scenario; and (5)–(8) are high nuclear power versions of the earlier scenarios. The low nuclear power assumption (120 GW) is based on the nuclear plants that are currently under application, construction and planning [90], while the high nuclear power assumption (200 GW) is based on a projection from others [91]. Detailed scenario assumptions can be seen in Table 4 and the resulting generation mix obtained by EnergyPLAN can be seen in Figure 1.

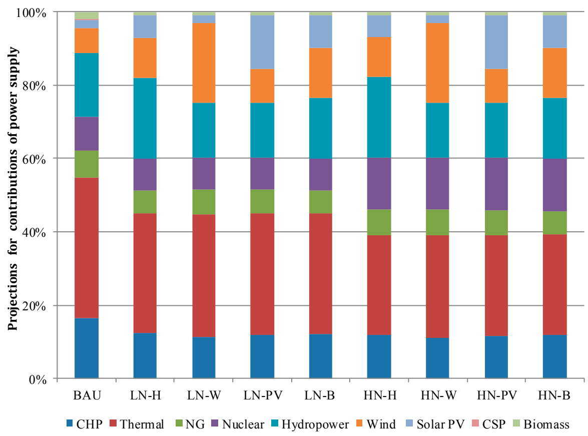


Figure 1. Nine projected electricity supply mixes for 2030.

Generation from coal (both thermal and CHP plants) is 4351 TWh as projected by Reference [57] for low nuclear power scenarios, and in high nuclear power scenarios, coal-fired thermal generation will be more replaced by nuclear power. For CHP plants, electricity efficiency and thermal efficiency is 35% and 42% respectively. Biomass power and CSP power retain the same share as the BAU scenario in alternative scenarios. The share of hydropower will decrease or increase depending on different installed hydropower potential by 2030. Generation rate from wind power and solar PV power increased inordinately due in the RES system as the main technologies to meet the target of 40% RE.

4.2.1. High Hydropower Scenario

In this scenario, the generation capacity of hydropower reaches 585 GW (the highest assumed capacity in existing literatures which is higher than technical potential) following [91], nearly all of the potential is developed. And hydro electricity production is 2106.8 TWh, accounting for 22% of electricity demand. As is shown in Figure 1, biomass power and CSP electricity production retain the same share as the base year (2015). The capacity of wind power increases to 400 GW (assumption from [33]) and electricity production is 1050.81 TWh with the correction factor projected by [87]. The remaining proportion is generated from solar PV. The rate of renewable electricity increases to 40% and nuclear power increases to 8.6%.

4.2.2. High Wind Power Scenario

Installed wind power capacity increases to 800 GW, in line with the government plans for 2020. This is in the middle of the basic and aggressive scenarios presented by China National Renewable Energy Centre [92]. The share of wind power increases to 22%, while hydropower declines to 15% as projected by [42]. Finally, generation from PV increases to 195 TWh, accounting for 2% in total generation to fill up the remainder of the 40% RE goal.

4.2.3. High Solar PV Scenario

Here installed PV capacity is assumed to reach 800 GW (1440 TWh produced per year) in line with the optimistic scenario by the China National Renewable Energy Centre [92]. Electricity production from hydropower and wind power is 1440 TWh and 897 TWh respectively. Technical assumptions are adopted from [87], including distribution of hydropower supply, wind power, and PV power supply, correction factors, and stabilization share for wind and PV power.

4.2.4. Balanced Mix Scenario

In this scenario, 80% of hydro potential is developed [57]. Installed capacities are 440 GW, 500 GW [41], and 480 GW for hydro power, wind power and PV, respectively. Contribution of hydro decreases, and wind power and PV increase to 15.6%, 13.7% and 8.8% respectively.

5. Scenario Evaluation and Comparison

Each of the scenarios was evaluated based on the five criteria: (i) total costs (ii) total installed capacity (iii) excess electricity and; (iv) CO_2 emissions; (v) direct job creation.

5.1. Scenario Evaluation

A system with 40% electricity from renewable energy can meet the climate target of 20% non-fossil energy in primary energy consumption (only the power sector) presented in the in INDC (Figure 2).

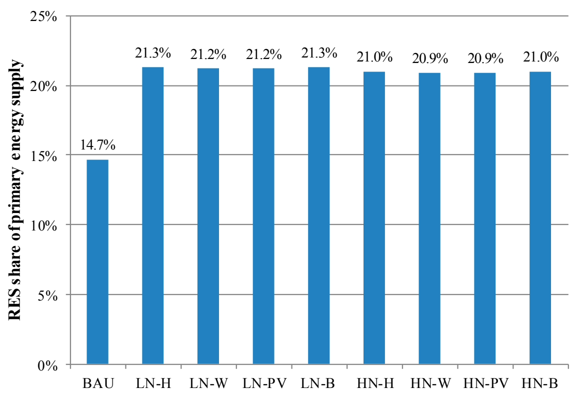


Figure 2. RES share in primary energy supply compared with BAU case.

5.1.1. Total Costs

Figure 3 shows the total costs of all scenarios in 2030 compared to the BAU scenario. All scenarios show higher costs. HN-PV requires the highest costs (469 billion USD using the exchange rate assumed by [93]) and this is 9.39% more than the BAU scenario. LN-W requires the lowest costs (421 billion USD), 1.84% less than the BAU case. High nuclear versions of the scenarios generally require more costs due to the replacement between nuclear power and coal-fired power. HN-H and HN-W scenarios are more economically sustainable than LN-PV and LN-B scenarios. This implies that only higher solar PV electricity systems are not suitable for China under current assumptions. Among the three kind of costs, annual investment costs mainly impact the differences among the eight alternative electricity systems.

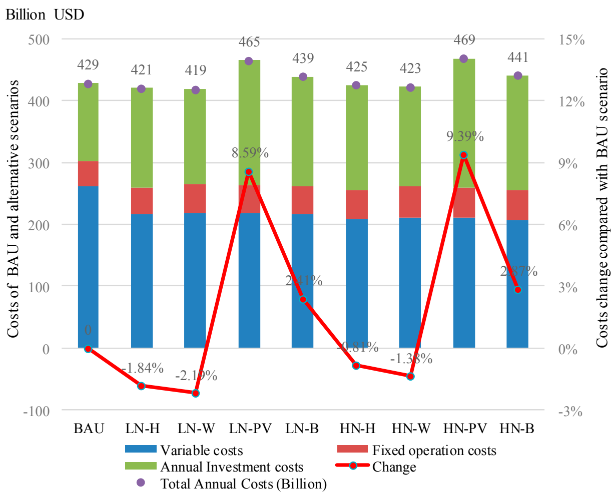


Figure 3. Total costs change compared with 2030 BAU scenario.

5.1.2. Total Installed Capacity

Figure 4 shows total installed capacity change compared with 2030 BAU case. It can be clearly seen that all scenarios require significant additions of installed power capacity. In the eight alternative scenarios, required total installed capacities are at least 30% or even higher than in the BAU case. PV-based systems have the highest total installed capacity requirements (2890 GW in HN-PV), 35.5% higher than BAU case. The LN-H scenario has the lowest total capacity requirement (2613 GW), only 22.6% higher than the BAU case. High nuclear power scenarios do not lower the total capacity requirements significantly, as more natural gas plants are required to maintain grid stability.

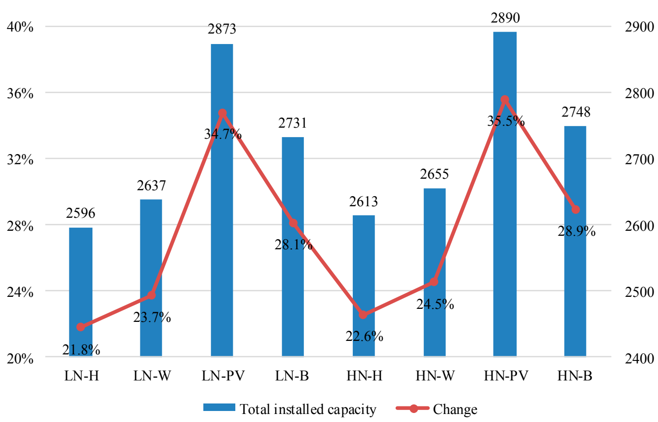


Figure 4. Installed total capacity change compared with 2030 BAU scenario.

5.1.3. Excess Generation

Figure 5 shows excess electricity exceeding the demand that generated in the various scenarios due to the fluctuating power output by wind and solar. The HN-W scenario produces most excess electricity (79.66 TWh), while the LN-H generates least excess electricity (3.87 TWh). There is no excess generation from the BAU case. When more coal-fired electricity is replaced by nuclear, it produces more excess electricity. EnergyPLAN seeks to use as more renewable power as possible and try to reduce the use of storable fuels [86]. When electricity production from wind and solar PV power cannot meet the electricity demand, PPs are used. However, in order to maintain stability of the grid, no less than 30% power of electricity from PPs is needed at all the times with voltage and frequency control capabilities but nuclear power plants are designed for stable production and assumed to produce stably in EnergyPLAN.

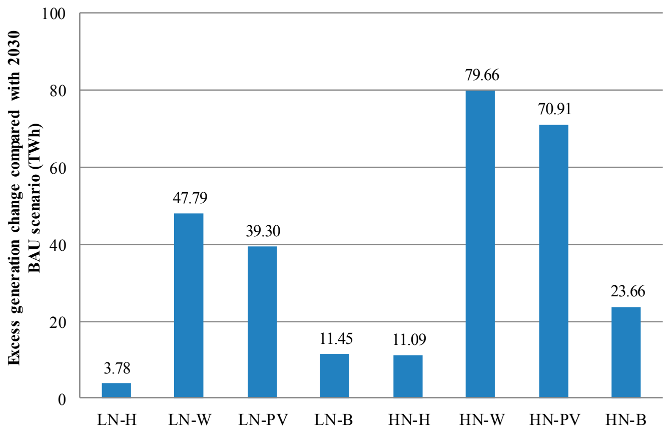
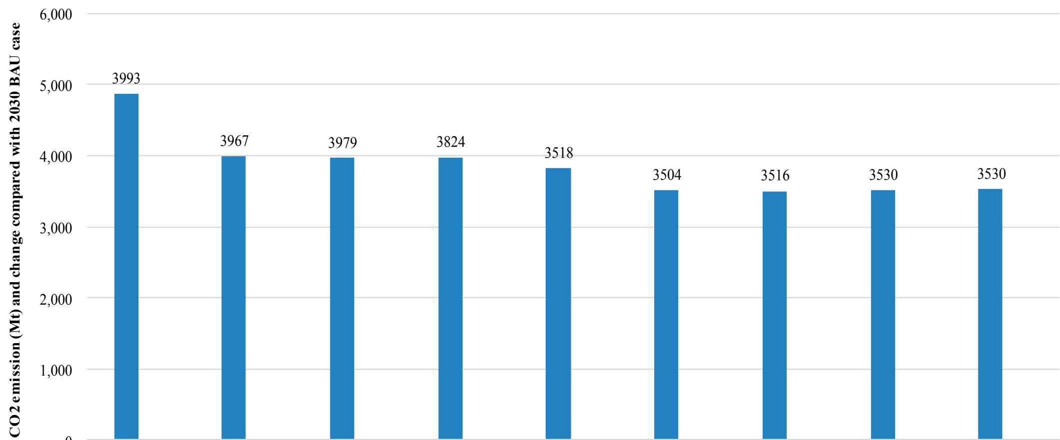


Figure 5. Excess electricity generation of the eight scenarios.

5.1.4. CO_2 Emissions

Resulting CO_2 emissions and change compared with the 2030 BAU case are displayed in Figure 6. Hardly surprising, all scenarios would lead to reduced CO_2 emissions compare to the base case. The results can be divided into two groups, high nuclear and low nuclear group. HN-H scenario has the lowest CO_2 emissions (3504 Mt) which could reduce 27.97% emissions compared with the BAU scenario. CO_2 emission is a constraint for planning in this paper and is not used for comparison between alternative scenarios.



	BAU	LN-H	LN-W	LN-PV	LN-B	HN-H	HN-W	HN-PV	HN-B
CO2	4865	3993	3967	3979	3824	3518	3504	3516	3530
Change	0	-17.93%	-18.47%	-18.21%	-21.40%	-27.70%	-27.97%	-27.72%	-27.45%

Figure 6. CO_2 emissions (Mt) and changes compared with 2030 BAU case.

5.1.5. Direct Job Creation

Direct job creation from eight alternative RES system are shown in Figure 7, all eight alternative electricity systems create more direct jobs than the BAU scenario. As can be seen, LN-H scenario provide 15.6% more jobs than BAU scenario and rank the first and HN-W scenario create only 1.4% more jobs. The two scenario create 2848 thousand and 2498 thousand jobs respectively. LN-H and HN-H would generate the most jobs compared to the other alternative scenarios.

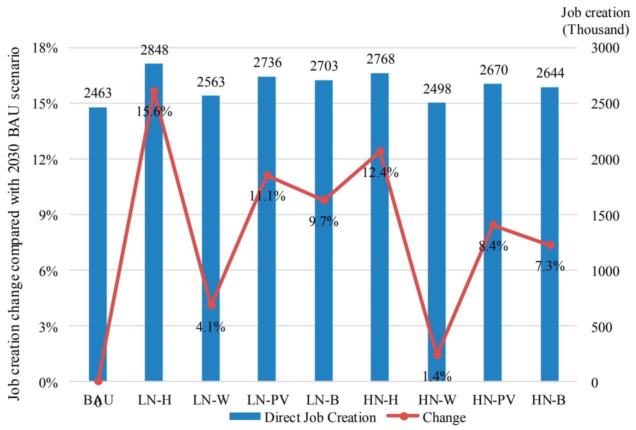


Figure 7. Direct job creation from eight alternative RES systems.

5.2. Sustainability Comparison of RE-40 Scenarios

Figure 8 show normalized impact values on the five evaluation indicators. The higher value means more sustainable at that dimension. It can be seen in Figure 8 that LN-H scenario shows the highest merits of for total capacity change, excess generation and job creation, but it can only reduce 34.14% of CO_2 emissions. It should also be noted that the hydropower scenarios systems imply that almost all available hydropower is developed. This would likely require significant policy support and planning.

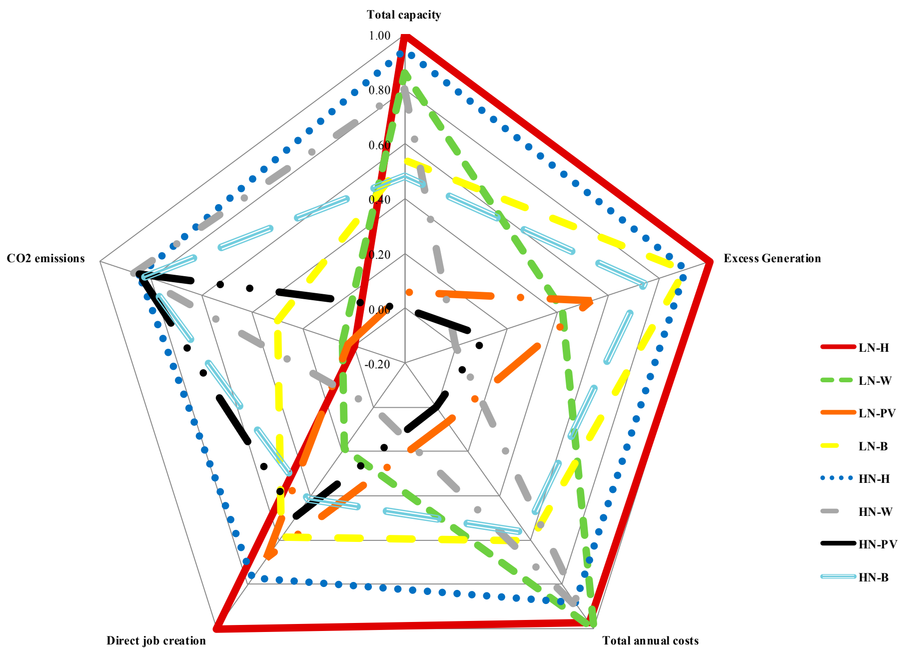


Figure 8. Sustainability comparisons of eight alternative RE-40 scenarios by normalized values of impacts.

If more CO_2 reductions are required, HN-H is the best option to achieve a RE-40 target and develop more hydro power plants. While if only 80% of total hydro potential could be developed, wind-based and balanced scenarios are good plans (LN-B, LN-W and HN-B). Wind-based RE-40 scenarios shows relatively better results across all criteria except for job creation, which could become an obstacle. Both LN-PV and HN-PV show the worst results almost in all dimensions, further indicating its limitations for an efficient transition towards a more sustainable energy system.

6. Conclusions and Policy Implications

This study reviewed renewable energy potential in China's power sector and applied EnergyPLAN and multi-criteria analysis to identify an optional renewable energy mix for the energy transition in China's energy sector in a system methodology. The main findings in this study are as follows:

(1) All eight alternative scenarios can achieve the goal of 20% share of non-fossil energy in primary energy system and 40%–50% share of non-fossil energy in electricity power.
(2) Low nuclear-hydro power scenario is the most sustainable scenario if it can be achieved. Taking the CO_2 emission reduction into consideration, HN-H scenario would be better.
(3) Analysis of LN-B scenario showed it to be comparatively sustainable energy system compared with other scenarios except for LN-H and scenario HN-H scenarios.
(4) The LN-W scenario requires the lowest electricity system costs. However, it would result in only a 1.4% job increase compared to the BAU case and would produce the most excess generation, which would be a complication with the rising share of renewable energy in total generation.
(5) Neither of the PV scenarios are that sustainable compared to the other scenarios. They show the highest costs (HN-PV), highest required total capacity, and second highest excess generation.

In the long run, hydro power cannot meet the demand for RE electricity production due to resource limitations. Considering these difficulties in achieving full development of hydro power, LN-H scenario (16.55% from hydro power, 13.72% from wind power and 8.79% from solar PV power) appears to be most preferable scenario for a Chinese RE-40 system. Even though China has abundant renewable energy, only relying on wind power or solar PV power is not a sustainable way for the future as found in our scenario evaluation. The results show that a replacement of fossil-fuel by nuclear to remit CO_2 emissions is with efficiency without regard to its impacts on excess electricity production [94]. The Chinese government should implement new policies aimed at promoting integrated development of wind power and solar PV. Furthermore, costs are barrier for the transition to cleaner energy. Reducing technical costs as well as creating new policies to balance grid costs should be explored as soon as possible, such as policies to promote clean coal use in coal-fired power plants [95] or Renewable Portfolio Standard in regional/provincial area. During the industrialization progress, China needs to carefully review and inspect the fossil energy-fired industrialized society that has arisen [96] and evaluate its impacts on sustainability development of energy system especially the power sector. This study is based on the national energy system, but it is strongly encouraging that more studies are done on regional level in the future given the importance of provincial decision makers in deployment of RE projects.

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Author Contributions: Xiaoyang Sun designed the paper; Baosheng Zhang took care of the literature review; Xu Tang provided the background and filtered the results; and Benjamin C. McLellan and Mikael Höök supervised the paper writing.

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Appendix A

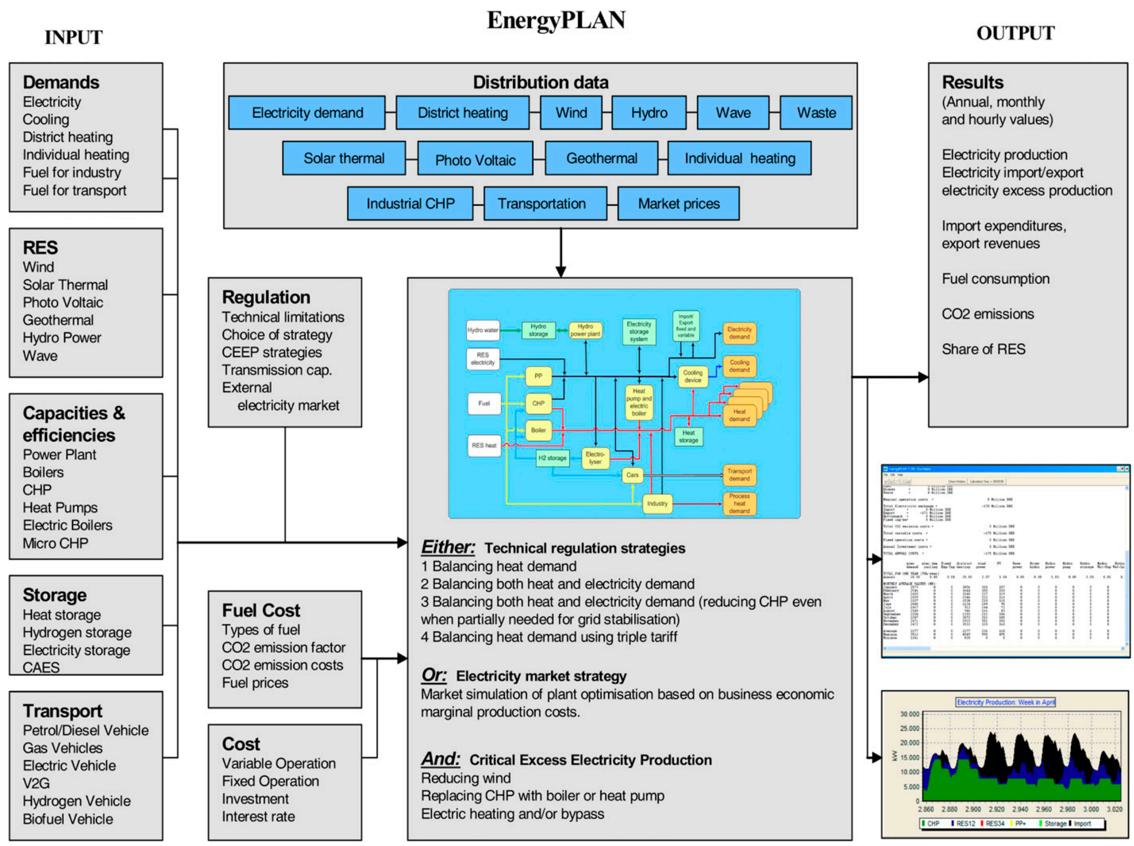

Figure A1. The structure of the EnergyPLAN tool [97].

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