Gleaning Experience from Danish Energy Transition for China's Carbon Neutrality

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Abstract. The transition towards sustainable energy is a prevailing occurrence, demanding an exchange of experiences and reciprocal learning on an international scale. Denmark, as a pioneer in the world's green energy transition, has many years of experience in energy transition and clean energy development. China should adopt a unique approach to accomplish the target of becoming carbon neutrality by 2060 while absorbing its advanced experience based on different national conditions. Based on China's national conditions, we propose three clean energy systems and provide sone optimization strategies under the framework of ENSYSCO which is based on power-to-x technology. In this manner, we are confident that it can provide a viable alternative for attaining carbon neutrality and ensuring efficient and secure integration of sustainable energy into China's power grid.

Keywords: Energy transition, clean energy systems, Carbon neutrality.

1. Introduction

1.1. The Effects of Global Warming, Clinate Change and the Conventions People Have Made

The accumulated impact of human life on our planet over the past several decades, and in particular the industrial revolution, resulted in a constant increase in greenhouse gas production (mainly CO_2) caused by the burning of fossil fuels [1]. More and more carbon dioxide accumulates in the atmosphere which causes the Earth's average temperature to rise and results in global warming and drastic changes to environment. The extreme weather happens more frequently year after year. The Internal Displacement Monitoring Centre (IDMC) estimated that there were 233.5 million internal transfers ot forced movements brought on by disaters between 2013 and 2022. Every year, millions of people are forced to relocate due to severe storms and flooding, droughts, earthquakes, tsunamis, and volcanic eruptions around Asia and the Pacific [2]. All countries around the world have recognized the necessity and urgency of addressing the issue of climate change.196 Parties at the UN Climate Change Conference (COP21) adopted The Paris Agreement. According to the Agreement, efforts will be made to keep the rise in the average global temperature well below 2°C and to keep it to 1.5°C above pre-industrial levels by advancing carbon peaking and carbon neutrality.

1.2. The Development of Danish Energy Transition and the Status and Strategies of Chinese Now and Future Energy Transition

Denmark acts as a global leader in the transition to green energy. In 2011, the Danish government published a series of agreements like "energy strategy 2050" with the goal of accelerating the growth of renewable energy particularly wind energy, biomass and other energy sources. All the measures were made to achieve the goal of completely phasing out coal as energy sources by 2030. On the basis of large-scale deployment of wind power in Denmark in the early years, the proportion of wind power generation now has reached over 50% and have great growing tendency. Nowadays, Denmark is committed to the transformation and application of energy technologies and is preparing to utilize the strategy of Power-to-X (PtX) to promote deep decarbonization of the future transportation and industrial sectors. All these measures enable Denmark to improve the ability of carbon capture and

strengthen multiple conversions of electricity. The ultimate goal of energy transition so to reach carbon neutrality by 2050.

The Chinese economy has developed by leaps and bounds during the last 40 years. However, the environmental problems also emerge along with it and they directly threaten sustainable development. China's endeavors to tackle climate change have garnered significant global interest ever since it emerged as the top contributor to carbon dioxide emissions back in 2006. The Chinese government has pledged to achieve carbon peaking by 2030 and attain carbon neutrality before 2060. As China's economy has transitioned into a period of reduced economic growth known as the "new normal" [3], it is vital to explore a path of economic boost with lower carbon emissions. China needs to make progress in four areas in the next 4 decades in order to reduce emissions specifically: energy use, energy efficiency, energy transformation, and negative emission technologies (NETs) [4]. However, when changing the energy structure and carrying out energy transformation, it is bound to face numerous challenges. Therefore, it is crucial for China to draw lessons from advanced international experiences. Denmark stands out as a country that has effectively completed an energy transition, shifting from almost complete reliance on fossil fuels to total renewable energy. As a result, Denmark can offer valuable insights for China's own energy transition. This paper begins by analyzing Denmark's successful energy transition, including its advantages and disadvantages. It then compares Denmark's situation with that of China and proposes suggestions for China to learn from PtX (Power-to-X) technology in order to achieve a sustainable energy transition.

2. Energy Transition in Denmark

In the early 1970s, oil accounted for more than 90% of Denmark's energy structure, making it the dominant source. However, the oil crisis in the 1970s had a significant impact on the Danish economy and energy supply. Since then, the Danish Energy Agency has been actively pursuing policy objectives to reduce oil dependence, energy consumption, and the loss of natural resources. In 1990, Denmark became the first country to develop a government plan to reduce carbon dioxide emissions, introducing comprehensive initiatives to lower carbon emissions and improve energy efficiency. In 2011, the Danish government introduced the 'Energy Strategy 2050' agreement, setting the ambitious goal of completely phasing out fossil fuels by 2050 and expanding renewable energy development. This plan was widely supported by most members of the Danish Parliament, who approved the complete phase-out of coal by 2030, a 70% reduction in carbon dioxide emissions by 2030, and achieving climate neutrality by 2050.

Denmark's energy transformation approach encompasses seven main aspects:

1) Establish an energy island
2) Invest in future green technologies to promote multiple conversions of carbon capture and electricity
3) Realize the green transformation of various industries
4) Improve energy efficiency and equipment renovation efficiency
5) Green heating, standardize the sustainable use of biomass energy
6) Develop green transportation
7) Promote green tax reform and improve the implementation of relevant policies

2.1. Denmark's Energy Transition Status

2.1.1. Energy transition and carbon peak

Denmark has successfully addressed this issue through a gradual phase-out of coal, cessation of nuclear energy utilization and robust promotion of renewable energy policies especially wind energy. These policies have led to a noteworthy transformation of Denmark's energy structure, shifting from reliance on fossil fuels to renewable sources. Since the inception of Denmark's energy policies in 1976, continuous refinement of new energy-related policies and technological advancements has yielded a positive impact on carbon emissions. Denmark's overall greenhouse gas emissions have

demonstrated a sustainable downward trajectory, as illustrated in the graph depicting total greenhouse gas emissions since 1990. The total national greenhouse gas emission in CO_2 equivalents excluding LULUCF (Land Use and Land Use Change and Forestry) has decreased by 41.3 % from 1990 to 2020, as shown in Fig.1. The emissions including LULUCF and indirect CO_2 have decreased by 42.5 % from 1990 to 2020.

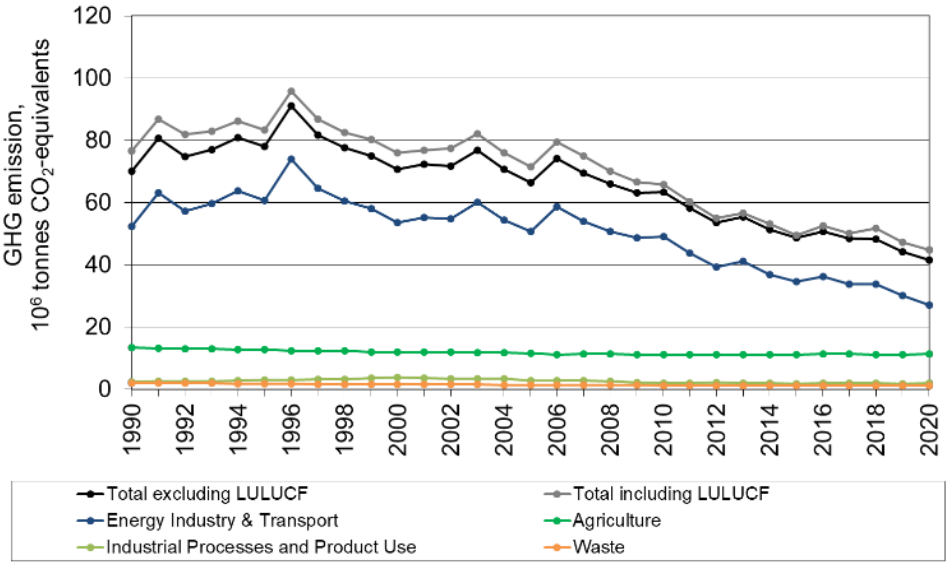

Figure 1. Greenhouse gas emissions in CO2 equivalents from 1990 to 2020 [5]

2.1.2. Energy consumption and production

Denmark maintains one of the lowest global levels of energy usage in relation to its gross domestic product (GDP), making it one of the world's most energy-efficient economies. Since 1980, there has been a notable 19% reduction in the overall consumption of primary energy sources. Compared to the year 1980, there has been a significant decrease of over 80% in coal consumption and a reduction of more than 50% in oil consumption observed in 2022. The proportion of renewable energy within Denmark's end-use energy consumption has steadily increased. At current stage, over 40% of Denmark's primary energy consumption originates from low-carbon sources and more than 25% of its end-use energy consumption is derived from renewable energy sources. Nowadays, the total electric energy consumption in Denmark is 33.08 billion kWh of electric energy per year. As a partly self-sufficient country, 28 billion kWh of all electric energy are produced in Denmark, which is 86 percent of domestic demand. The rest is required to import from foreign countries [6]. From the perspective of electricity supply, Denmark witnessed an 18% increase in electricity generation in 2022 compared to the levels recorded in 1990. At the same time, the share of electricity generation sourced from coal, gas and oil experienced a substantial decline of 78%. And over half of the domestic electricity production is derived from renewable energy sources, predominantly wind power energy. Presently, Denmark boasts an onshore wind power energy capacity exceeding 5GW accompanying with an offshore wind power energy capacity of nearly 1.3GW. During periods of ample wind resources, the electricity output from Danish wind turbines is capable of fulfilling or potentially surpassing the nation's domestic power demands.

2.1.3. Social-economic development after carbon peak

Driven by proactive energy policies, Denmark has placed considerable emphasis on enhancing energy efficiency and vigorously advancing renewable energy while ensuring the cost-effectiveness. This approach has not only reduced reliance on fossil fuels, but it has also led to significant economic growth. Moreover, it has also achieved the goal of environmental conservation and contributed to the mitigation of climate change. Following the attainment of its carbon peaking in 1998, the per capita GDP of Denmark has exhibited a consistent upward trajectory, escalating from 223,000 US dollars to 473,900 US dollars in 2022.

2.2. Main Energy Transition Approaches in Denmark

The key factors contributing to Denmark's prominent role in the energy sector are the continuous research, development, and implementation of new technologies and systems. This progress has been facilitated by effective collaboration between the public and private sectors, within a stable political environment and strong regulatory framework. Currently, Denmark is strategically working towards a low-carbon transition in its energy sector, with a specific emphasis on electrification and energy efficiency through system integration.

2.2.1. Electrification of energy

Between 1990 and 2020, the reduction in carbon emissions from power generation and district heating has played a crucial role in shifting the focus of emissions reductions towards the agricultural and transportation sectors to achieve climate targets. Fig. 2 illustrates that Denmark's electricity and heat production sectors have made significant progress in decarbonization, providing a solid foundation for the direct electrification of other industrial processes. It also predicts the expected breakdown by sector in 2030.

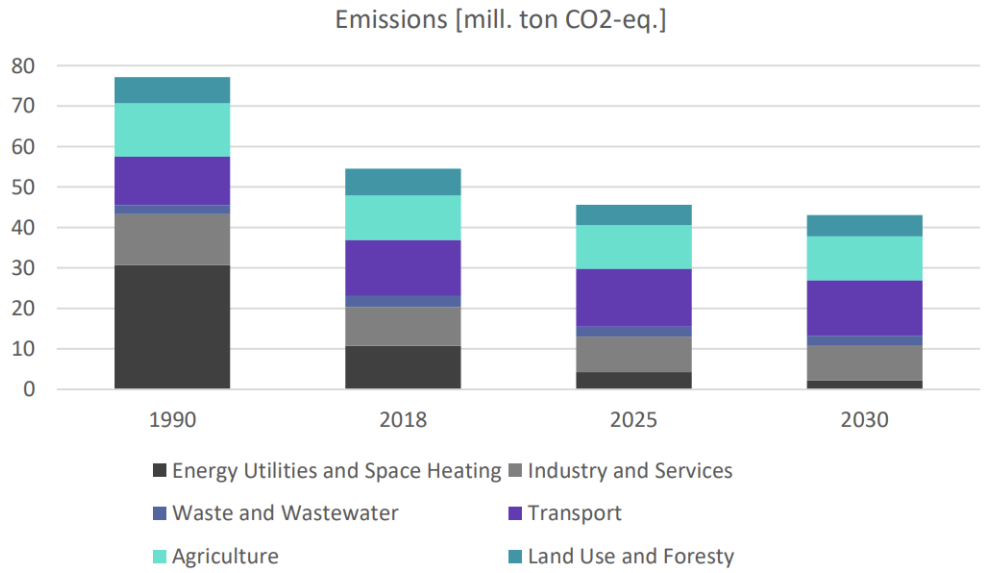

Figure 2. Total emissions by sector 1990-2020 [7]

Currently, the transportation sector is responsible for 26% of all carbon emissions, indicating that the success of Denmark's climate objectives depends on transforming road transportation. The Danish government has prioritized electrification within this sector, aiming to have one million low-emission vehicles by 2030. By 2027, a significant portion of the Danish state railway network is projected to be electrified. It is worth noting that there has been notable progress in electrification in the road transportation sector. In the period from October 2021 to September 2022, plug-in hybrid electric vehicles (PHEVs), electric vehicles (EVs), and other low-emission vehicle types made up 39.1% of all newly sold vehicles. Additionally, a total of 1,756 km of railway track has already been electrified.

2.2.2. Improve energy efficiency and reduce energy consumption

In Sadamori and Motherway's study conducted by the International Energy Agency, it is emphasized that energy efficiency plays a crucial role in achieving a sustainable energy transition [8]. Enhancing energy efficiency has been recognized as a key objective in the European Union's sustainable development agenda until 2020 [9]. Energy intensity and carbon intensity have frequently been used as an index for a country's energy efficiency. A lower energy intensity indicates it needs less energy per unit of GDP. And a lower carbon intensity means less amount of carbon emitted per unit of energy. From 1990 to 2020, the energy intensity of Denmark has dropped by 50% and the carbon intensity of Denmark has declined by more than 30%. Both indicators provide powerful evidence of the increase of energy efficiency.

A political agreement has been established in Denmark to work toward the objectives of generating all of its electricity from renewable sources and raising the share of renewable energy in its total energy consumption to 55% by 2030. Additionally, the Danish government is dedicated to achieving energy self-sufficiency through renewable sources by 2050. It is worth noting that the country has managed to reduce its total energy consumption by 6%, with a decrease from 424,000 TJ in 1990 to 398,000 TJ in 2020. And the share of renewable energy has reached to 45% in 2020. The statistics indicate that Denmark's ongoing efforts to enhance energy efficiency and decrease energy consumption have shown significant progress. It is crucial to maintain these efforts consistently.

2.2.3. Combined heat and power (CHP)

Denmark's energy paradigm prioritizes energy system integration and development, demonstrated by the simultaneous production of electricity and heat in the power generation and district heating sectors. The country effectively reduces overall energy consumption by utilizing centralized district heating to distribute thermal energy. Cogeneration of power and heat plays an essential role in lowering Denmark's carbon dioxide emissions. The widespread utilization of combined heat and power plants with heat storage capability and the expanding use of wind power present substantial promise for the effective integration of heat and electricity networking. Wind power energy is Denmark’s most dominant renewable energy source. Given that wind power generation occasionally exceeds domestic electricity demand. Denmark utilizes a range of innovative technologies to improve the efficiency of cogeneration and integrate large proportion of fluctuating wind power energy. Through the use of small-scale cogeneration power plants which modulate the ratio of heat and electricity production, the system is able to reduce electricity supply and still maintain a consistent heat supply when wind power energy supply surpluses. Additionally, thermal power plants are able to adapt the daily power generation levels as quick as possible in response to fluctuations in wind power energy in result of improving plant efficiency.

2.3. Major Development Plans in Denmark

In 2020, the Danish Government reached an agreement to prepare a Danish strategy for Power-to-X (PtX) and Carbon Capture and Utilization (CCU). Firstly, Denmark has built the necessary framework conditions for PtX to make it fuuly realize its commercial environmental potential at the same time. Power-to-X is a transformative solution which indicates diverse ways to generate energy [9]. X can stand for various products, applications, processes and technologies. Fig. 3 shows the flowchart of Power-to-X with the usage of renewable energy.

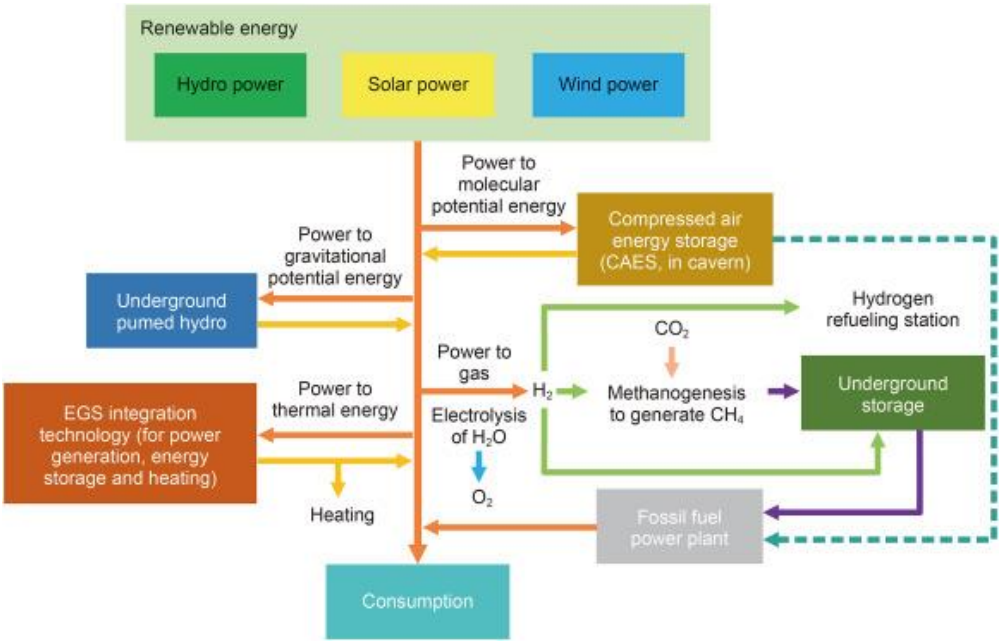

Figure 3. the flowchart of Power-to-X [11]

As demonstrated by Fig. 3, green hydrogen produced by water electrolysis functions as a versatile energy carrier is able to be applied in multiple sectors. Power-to-X (PtX) presents environmentally friendly solution that offer advantages to both the citizens of Denmark and the global community. The Danish government schedules to establish two energy island projects, one is located in North Sea and the other is set near the Baltic Sea. The installed capacities of these projects will be 10 million kilowatts and 3 million kilowatts, respectively. These projects aim to become significant offshore wind power aggregation stations, using wind and solar energy to produce hydrogen. The hydrogen generated will be transmitted to infrastructures or directly synthesized into fuels. Moreover, the energy islands will also act as nodes in offshore power transmission networks, connecting the electricity systems of neighboring countries. The progress of these energy island projects will play a vital role in advancing PtX technologies.

In the context of carbon capture, utilization, and storage (CCUS) technologies, the Danish government is primarily prioritizing biogenic sources. As part of this effort, they are in the process of developing appropriate regulatory frameworks to achieve a reduction potential of 1.4 to 6.5 million tons of carbon dioxide equivalent by 2030.

3. Experience from Denmark Energy Transition for China’s Carbon Neutrality

The carbon-neutral strategy proposed by China primarily encompasses two aspects: the reduction of carbon emissions and the enhancement of carbon absorption. By incorporating insights from Denmark's experience and evaluating China's unique circumstances, it is anticipated that the forthcoming carbon-neutral technological pathways will encompass the subsequent three elements:

1) Energy efficiency should be priorly considered to be improved. China has set up the goal to increase the proportion of non-fossil energy share up to 85% in the energy structure by 2060.

2) Electrification should gain more popularity in all industries. China aims to achieve the electrification rate of 70% by 2060.

3) Green power supply should be universally applied. 12 billion tons of carbon emission in 2030 should be taken down to 2.4 billion tons in 2060.

3.1. Experience from Danish Energy Transition

In order to achieve sustainable GDP growth, improve energy efficiency, increase electrification rate, and develop new energy sources, China can draw lessons from the Danish model for its energy transformation strategy. One approach that China can adopt is the development of a smart grid system to enhance the proportion and efficiency of renewable energy. Additionally, China should formulate policies that are responsive to market changes to ensure the sustainability of renewable energy development. While China may not have the same offshore wind power resources as Denmark, it does possess a diverse range of energy resources, including abundant renewable energy with uneven distribution, as well as less reliance on oil and gas compared to coal. As a result, it is advised that China take the lead in actively advancing renewable energy technology, progressively raising the share of renewable energy, and lowering the dependency on fossil fuels.

3.2. China’s Opportunities in Carbon Neutrality

China's journey towards carbon peaking and carbon neutrality presents both opportunities and challenges. China will give priority to the advancement and industrialization of green innovation through the production of low-carbon and zero-carbon technologies. The objective is for China, which presently imports the highest amount of fossil energy globally, to transform into the principal provider of new energy. Remarkably, within the previous 12 years, China's participation within the supply chain of solar panels has surged from 55% to 84%. Additionally, the wind power industry in China has experienced remarkable growth in 2020-2021, with double the new installed capacity compared to 2019. The installed renewable energy capacity in China has doubled between 2017 and 2022. However, the power generation from renewable energy sources has not increased proportionally,

indicating that the efficiency of renewable energy needs improvement. Therefore, it is crucial to focus on optimizing the utilization and energy storage capacity of renewable energy.

4. Energy Transition Strategies for China

4.1. Construction of Clean Energy System

With a land area of 9.6 million square kilometers, China has unique natural resources [12]. The eastern and northern regions have favorable sunshine conditions for photovoltaic development. The 12 provinces in wastern China including both municipalities and autonomous regions possess hydropower resources that make up approximately 30% of the national total, with the potential to develop over 80% of this resource. Additionally, the northwest and coastal regions have an abundance of wind resources that can be used to generate wind energy.

4.1.1. Hydropower plant system

Hydropower presents itself as a promising solution for decreasing dependency on fossil fuels and addressing the challenges of climate change, owing to its numerous merits including cleanliness, low carbon emissions, affordability, dependability, and adaptability [13]. China is known for its abundant river basins and is a global leader in terms of water resource reserves, hydropower capacity, dam construction, and hydroelectric generation. The hydroelectric power sector in China has experienced significant growth over the past few decades, benefiting from its well-established renewable energy source and advanced technology. From Fig. 4, it is obvious to see that China's hydroelectric power generation consistently expanded from 2011 to 2020.

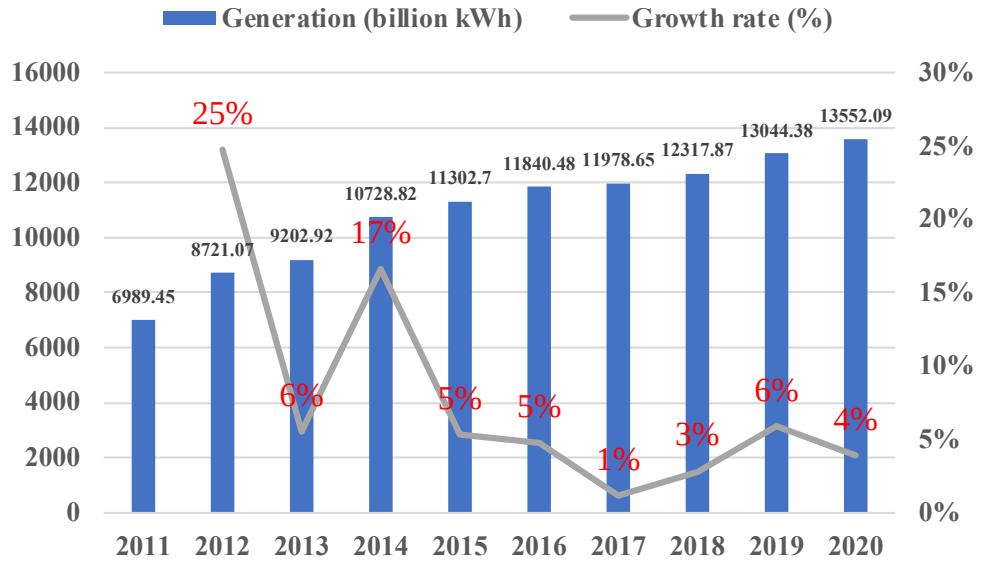

Figure 4. China's hydropower generation and growth rate from 2011 to 2020

The 2020 white paper "Energy in China's New Era" indicates hydroelectricity's dominant position in the energy supply system. However, during the development of hydroelectric technology, several challenges still need to be addressed. One significant issue is energy waste, which remains a concern. Additionally, the overall operational efficiency of hydroelectric plants is not yet optimal. Moreover, the construction of hydroelectric facilities inevitably leads to negative environmental impacts in their surroundings.

4.1.2. Wind power system

Wind power is one of the most promising renewable energy technologies in the future [14]. China possesses abundant wind energy resources with significant untapped potential. Since the implementation of the Renewable Energy Law in 2005, the wind power industry has experienced

rapid growth and has established a prominent position in the sector. China has gradually grown its wind power production in recent years, albeit the growth rate varies on an annual basis. (see Fig. 5).

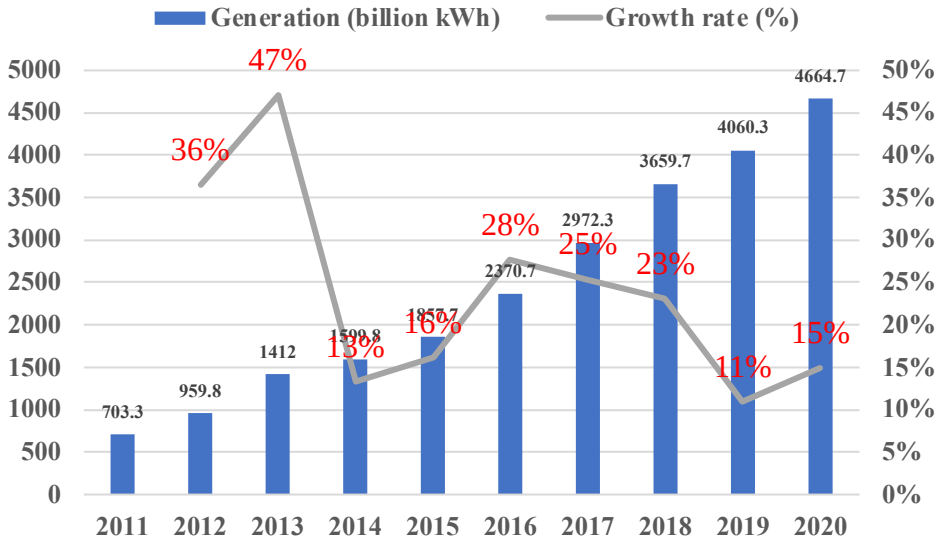

Figure 5. China's wind power generation from 2011 to 2020

However, the inherent randomness of wind resources leads to significant fluctuations in wind power generation. As wind power projects grow in scale, the complexity of power system dispatch also increases, leading to a higher occurrence of curtailment, reduced energy efficiency, and operational challenges. Given this, it is imperative to continue developing large-scale and highly concentrated wind power projects.

4.1.3. Photovoltaic power generation system

Solar energy is an inexhaustible clean energy that does not pollute the environment [15]. China is abundant with solar energy resources. However, the need of the European market was what propelled its photovoltaic power generation sector. Solar energy has steadily gained increasing attention in China just in recent years. From 2017 to 2020, China's photovoltaic energy output climbed by more than two times. (see Fig. 6).

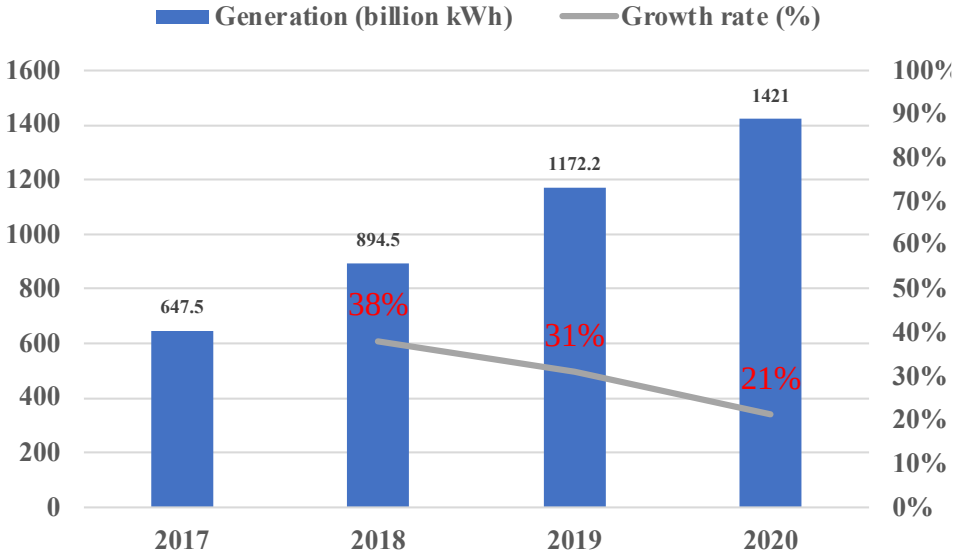

Figure 6. China's photovoltaic power generation and growth rate from 2017 to 2020.

China currently has abundant untapped solar energy resources. However, there is a disparity between regions with high solar photovoltaic (PV) potential and areas of concentrated population, as well as regions with elevated electricity demand. Therefore, the establishment of cross-regional power system configurations becomes crucial for the further development of the solar PV industry.

4.2. Clean Energy Systems Based on ENSYSCO Framework

In order to achieve carbon peaking and carbon neutrality, the primary battleground lies in energy, while the predominant strength is derived from power. It is the key point for China to build a fresh power system centered on renewable energy along with driving the comprehensive transition of energy usage across sectors like transportation and industry. Currently, while renewable energy generation technology has reach maturity, other areas like construction and transportation are still dominated by fossil fuels. In this circumstance, Chinese government has proposed several solutions to meet the needs of energy transition. In the pursuit of balancing economic growth with carbon emissions limitations, the enhancement of energy system efficiency, particularly in terms of end-use energy efficiency, is a crucial factor. Besides, future energy systems will have a distinguishing feature that renewable energy takes the leading position. And different types of renewable energy generation plants which are located in different environmental conditions have variable productive potential. Therefore, aiming at the goal of overall transformation of energy system, it is urgent to establish a unified overall clean energy system. A comprehensive future framework called "Clean Energy Systems based on Smart Sector Coupling" (ENSYSCO) was proposed by Hou and Feng [16]. Based on Power-to-X, the ENSYSCO architecture unifies the three primary energy production, consumption, and storage sectors. Besides, it also employs power multi-conversion/reversal technology and semi-physically driven AI and Big Data based systems to achieve power-to X-to-power process in order to manage and analyze production, consumption and energy storage across transport networks and grids. By using ENSYSCO framework, the considerable electricity waste caused by uneven distribution of renewable energy can be alleviated.

5. Conclusion

Denmark's energy transition has been widely regarded as a successful exemplar across multiple dimensions, including energy planning and legislation, policy execution, as well as the development and deployment of clean energy technologies. China has the opportunity to gain valuable insights from Denmark's energy transformation experience, focusing on three key areas: (1) Aligning the energy transition pathway with China's energy resource distribution; (2) Facilitating the electrification of the transportation sector; (3) Promoting the widespread adoption and advancement of renewable energy and associated technologies, along with gradually reducing dependence on fossil fuels. The development of China's sustainable energy system can be enhanced by leveraging the ENSYSCO framework. This framework enables the optimization and allocation of power networks in the areas of production, consumption, and energy storage. The significant progress in clean energy not only accelerates China's shift towards a low-carbon energy landscape but also creates promising opportunities for the implementation of new energy technologies.

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