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Review article

Comparing the energy transitions in Germany and China: Synergies and recommendations

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ABSTRACT

Energy Transition towards a low-carbon emission energy system has been a long-term strategy for Germany and China. Both countries are expected to take the lead on the global effort to achieve clean energy and greenhouse gas emissions reduction. Although Germany and China have different characteristics, international-level strategic cooperation is essential for meeting the goals of both local and global energy transition. However, until now, no comparable research for energy transition in Germany and China exists in a peer-reviewed journal. In order to close this knowledge gap, a critical review was conducted and then some recommendations were proposed. First of all, after reviewing the background, milestones, current situation and challenges, we found infrastructure, policy instruments and market reform played the key roles in the transition process in Germany and China. While nuclear power and coal are likely to be abandoned in Germany, China has more ambition beyond the power sector and to reach self-sufficiency. As the two countries chosen different concepts and pathways to achieve their transition targets, there is great opportunity for them to take the lessons from each other. Germany and China need cooperation at multi-levels varies from politic, economic, scientific to public. Then, recommendations are presented on how to further foster cooperation and enable an energy transition.

Contents

0. Introduction

As global warming affects the long-run sustainability of human beings regional-crossly, it can only be tackled in a conjoint

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international effort. The *Paris Agreement* links the upper limit with a specific action target: global greenhouse gas (GHG) neutrality by the second half of the century (UNFCCC, 2015). Given the fact that around two-thirds of GHG emissions from energy production and utilization, energy decarbonization has been increasingly critical for addressing the low-carbon development responding to climate change mitigation. This can only be achieved with the massive deployment of renewable energy combined with energy efficiency (IRENA, 2017). Just a few months before the Paris climate conference, the international community, meeting in New York in September 2015, adopted the *2030 Agenda for Sustainable Development* with its 17 Sustainable Development Goals (SDGs) (UN, 2015). Energy lies at the heart of these SDGs, particularly in the goals of energy access, climate mitigation, lower air pollution, as well as for sustainable urbanization and industrialization. Under such circumstances, the global energy system must undergo a profound transformation, from one based mainly on fossil fuels to one that enhances efficiency and is based on renewable energy (IRENA, 2018).

Sustainable energy transitions, which broadly described as moving away from fossil fuels towards renewable resources and reducing energy demand, are emerging across the world, albeit in uneven ways (Dowling et al., 2018). Germany is widely considered a pioneer when it comes to energy transition (Knopf and Jiang, 2017). In line with international trends, Germany had set up an ambitious plan for climate protection, aiming to reduce Germany's GHG emissions by the year 2020 by 40% compared to 1990, until 2050 by 80 to 95% (BMU, 2016). As a critical aspect of the plan, the German energy transition (known in German as "Energiewende"), laid important groundwork to reform the energy sector, as well as for demonstrating energy transition practice at the global level (Gao et al., 2018). The Energiewende is an integrated policy framework, covering all sectors of energy and economy, including the targets and policy measures for CO_2 emission reduction, renewable energy development, phase-out nuclear energy by 2022, and improvement of energy efficiency (Haas, 2018; BMWi, 2018). For example, with its national support scheme for renewable energies, Germany has made a substantial contribution to the global technological development of wind power, photovoltaics, and the associated cost depression (Lutz et al., 2017). Furthermore, the Renewable Energy Act (in German: *Erneuerbare-Energien-Gesetz*, abbr.: EEG) serves as a model for other countries around the world, and the German government has a proven track record of supporting the global expansion of renewable energy (Quitzow et al., 2016a).

The global energy transition, however, has more than one pioneer, particularly in the field of developing renewable energy. As the world's biggest energy consumer, China accounted for 23% of global energy consumption and contributed 27% to global energy demand growth in 2016 (IEA, 2017), therefore, China's role in global energy transition is critical in determining global trends due to the scale of China's clean energy deployment, technology exports, and outward investment (Liu et al., 2018). In June 2015, China officially committed to achieve the peaking of CO_2 emissions around 2030 and make best efforts to peak early. China also committed to lower CO_2 emissions per unit of GDP by 60% to 65% from the 2005 level and increase the share of non-fossil fuels in primary energy consumption to around 20%. As a result, China's development of non-fossil energy (renewable energy and nuclear power) is rapidly being promoted. In 2017, China accounts for a record 45% of global investment in renewables (excluding hydropower larger than 50 MW), up from 35% in 2016 (REN21, 2018). The International Energy Agency predicted that China alone is responsible for 40% of global renewable capacity growth between 2017 and 2022 (IEA, 2017). However, the lack of successful transition experience also makes the government less confident in facing the output uncertainty and variability of renewable energy.

In general, German energy transition and Chinese energy revolution share three similar goals, namely reducing GHG emissions, expanding the use of renewable energy and increasing energy efficiency. On top of those, affordable and secure energy supply is also a clear strategic goal for both countries. However, China uses the term of "Energy Revolution" instead of the internationally well-accepted term energy transition. Literally speaking, revolution is a stronger expression than transition, reform or change. Therefore, some Chinese researchers claim that revolution can demonstrate the determination of the Chinese government in reforming the energy sector (Wu and Zhan, 2013). The differences are more than just terminology. While the Energiewende in Germany highlights the efforts in the electricity sector, China has ambitions in also transforming the transportation sector towards renewables. Such common ground and differences make it potentially possible and profitable for the two countries to cooperate in diverse ways.

After the withdrawal of the United States from the Paris Agreement, China and Germany are acting more ambitiously on the leadership of climate protection and energy transition (Knopf and Jiang, 2017). The governments of Germany and China have vowed to intensify their joint efforts in global climate diplomacy and in upholding free trade, as well as in the development and rollout of energy transition technologies. In a joint statement on the occasion of the 4th German–Chinese Intergovernmental Consultations, which was co-chaired by Chinese Premier Li Keqiang and German Chancellor Angela Merkel, the two countries announced that "both sides welcome the innovative cooperation between universities, research institutions, and companies from both countries in the field of sustainable energy. Both sides will work to boost cooperation in the fields of improving energy efficiency and expanding renewable energy".

In principle, the issue of energy transition is related to global political and technological transformation; no single country can formulate and successfully implement its plan. Therefore, strengthening the multi-level understanding and strategic cooperation at the international level is essential for meeting the goals of energy transition. In other words, it is entirely necessary to examine and analyze the energy transition from a comparative perspective (Marquardt et al., 2016). In contrast to the growing cooperation at the political and public level, scientific communities had not contributed enough in mutual understanding and to monitor the policy environment in both countries. Only recently, energy transition policy has become the subject of scientific papers in Germany and China (Quitzow, 2016b). We found that, until now, no comparable research for energy transition in Germany and China exists in a peer-reviewed journal. In order to fill this knowledge gap, this paper aims to examine the policy of energy transition in Germany and China from a comparative perspective and offer synergies for better cooperation.

1. An overview of energy transition in Germany

1.1. Background: with a focus on the driving forces

In 2010, Germany set up a plan to achieve its energy transition with short-term and long-term targets for the pathway to 2020, 2030, 2040 and finally increasing the share of renewables in power consumption by 80% in 2050. As an integrated policy framework covering all sectors of energy and economy, this policy is now widely known as the German energy transition (the so-called Energiewende). However, this energy transition already started with the introduction of fixed feed-in-tariffs for renewable energy long time earlier. In the wake of the nuclear accident in 2011, a more rapid transition was triggered and the decision was then taken further to phase-out nuclear power by 2022. It is considered an ambitious industrial project and requires technical and societal transformations, ultimately not only within Germany but in the whole of Europe. While discussions of the Energiewende in Germany reveal diverse viewpoints about goals and prioritization, CO_2 emission reduction, renewable energy development, phase-out nuclear energy, and improvement of energy efficiency were virtually accepted as driving forces and targets (see Table 1). In 2014, the previous Federal Minister of Economy and Energy, Sigmar Gabriel, has declared the following five goals for the Energiewende: (i) nuclear phase-out, (ii) the reduction of dependence on imported oil and gas, (iii) the development of new technologies, growth and new jobs, (iv) climate change mitigation, and (v) motivation of others to imitate the Energiewende (Gabriel, 2014).

1.2. Milestone

The Energiewende can be taken as a series of federal laws that build on each other, each one adapting to current realities while maintaining focus on the long-term vision. With the support from EEG, the share of renewable energy sources in power sector has been growing significantly, with the proportion of renewable energy in gross power consumption (total volume of electricity consumed in Germany) increase from roughly 6% in 2000 to 31.5% in 2016. The purpose of it is to enable a sustainable energy supply system, in line with climate mitigation and environmental protection goals, to reduce the costs of energy supply, to conserve fossil energy resources, and to promote technology development for renewable energy sources. Importantly, the EEG and its amendments in 2004, 2009, 2012, 2014 and 2017 have set up the main target in reaching the minimum shares of renewable energy in electricity supply pathway to 2050.

In September 2010, the Energy Concept, a comprehensive new strategy and the basis guiding its energy transition have been adopted. The Energy Concept provides a long-term strategy for Germany to become an energy efficient and environmental-friendly economy while maintaining competitive energy prices and a high level of prosperity. Following the Fukushima nuclear accident, the Energy Concept was updated in 2011, aiming to accelerate the phase-out of Germany's nuclear fleet by 2022 (Table 2). In November 2016, as one of the first countries submitted its long-term development strategy for achieving low GHG emission to the UN as required under the Paris Agreement, German government adopted the Climate Action Plan 2050, making Germany one of the first countries to submit the long-term Climate Action Plan 2050. In particular, it set up a target for reducing GHG emission in general and in various economic sectors, in order to reach its 2050 climate goals.

1.3. Status quo

To understand where Germany stands in its energy transition, one needs to look at the energy system as a whole, in particular, final energy consumption, how much different end consumers use energy, and energy production, which sources of energy make up the national energy mix (Fig. 1) (AGEB, 2018). The expansion of renewable energy is a central pillar in the energy transition of Germany. In recent decades, Germany has significantly diversified its electricity mix towards renewable energy, which grew from 4 percent in 1990 to 33 percent in 2017 (Fig. 2). However, the share of renewable energy in other sectors (transport and heating/cooling) has not increased proportionally due to a strong focus on the electricity sector.

To get an idea where the energy transition in Germany stands right now, Fig. 3 depicts the primary energy consumption in 2017. Though renewables account for 13%–14% of the total primary energy consumption biomass still dominates the renewables share and wind, solar and solar thermic make only up for about 4% combined. It shows, that despite enormous efforts, it is still a long way to go for Germany to achieve the goals it set. Not surprisingly, looking at these numbers Germany sled back on its goals for 2020 recently, and simply postponed them. Please notice that Germany so far spent more money on subsidizing coal in the past than to promote renewables via the renewable energy act.

Throughout the energy transition process, the German government have been working on the basis of an "efficiency first" principle and has been seen it as "the only way to adequately limit demand and ensure that the increased use of renewable energy can be carried out in a way that conserves resources and does not impact negatively on nature". Germany not only increases the share of green energy in its supply but also uses energy more economically. Primary energy consumption has been cut significantly in recent years in Germany, by 7.6% between 2008 and 2015 (BMWi, 2016).

1.4. Challenges

Many challenges lie ahead to transform the entire system. These challenges range from grid infrastructure and digitization to market design. As wind, solar, hydro and geothermal energy are fluctuating sources, the dispatching and absorption energy system needs to adjust accordingly and offer flexibility to guarantee a reliable supply. Technologies need to be developed to make other energy resources as complements and make traditional cogeneration plants to work more flexibly. Furthermore, expanding wind and solar power production will lead to growing supplies of excess power. Therefore, energy storage technologies and innovative transform solutions like power-to-gas will be also in needed. Additionally, demand-side management is a key for energy efficiency. Some power consumers already adjusted their power consumption to supply. In the future, all consumers, from private households to industrial large-scale consumers, will play a role in the power market by responding to supply.

"The Energiewende will succeed if we make progress with the grid extension", Germany's new Federal Minister for Economic Affairs and Energy, Peter Altmaier, said simply, in his first speech to parliament in March 2018. The energy transition's big success to date is the rapid growth of renewable power generation, which covers almost 40 percent of German power consumption in early 2019 — up from 3.2 percent in 1991 (ZSW, 2017). However this also poses a problem due to the vast number of decentralized renewable energy installations and how the grid operators have to deal with integrating these because they are forced to by law, possibly leading to necessary investments in grid upgrades that have to be reimbursed and finally be paid by the consumer via the grid fee that is part of the electricity bill (Matchoss et al., 2019; Bayer et al., 2017). The biggest share of renewables in the electricity sector is wind, mainly generated in the country's north, and in order to make proper use of it, high capacity transmission lines have to be built connecting wind farms in the north with the entry point of former fossil and nuclear power plants in the more industrial south and west of the country leading to a number of acceptance issues due to visual and environmental impacts, cost and building density in Germany that complicates finding a proper route, and already led to a new federal regulation that favors cables over overhead lines (Thomas et al., 2016).

Among the three elements of the government's so-called energy policy target triangle, supply security, affordability, environment and climate, a monitoring report noted the biggest failure in addressing climate protection sufficiently (BMU, 2018).

Table 1
Key German energy transition targets.
Source: Date source: The Sixth "Energy Transition" Monitoring Report (BMWi, 2018).

	Target	2016	2020	2030	2040	2050
GHG emission	(compared with 1990)	−27.3%	−40%	−55%	−70%	−80% ∼ −95%
Renewable energies	Share of gross electricity consumption	31.6%	35%	50%	65%	80%
	Share of gross final energy consumption	14.8%	18%	30%	45%	60%
Energy efficiency	Primary energy consumption (compared with 2008)	−6.5%	−20%			−50%
	Gross electricity consumption (compared with 2008)	−3.6%	−10%			−25%
	Primary energy consumption in buildings (compared with 2008)	−18.3%				−80%
	Heat consumption in buildings (compared with 2008)	−6.3%	−20%			
	Final energy consumption in the transport sector (compared with 2008)	4.2%	−10%			−40%
Nuclear phase-out	Gradual shut down nuclear power plants by 2022					
Electric vehicles	One million electric vehicles on the road by 2022					

Table 2
Overview of major energy policies and strategies in Germany.

Publication year	Document title	Key context
2000	Renewable energy act (EEG)	EEG implements a fixed feed-in tariff for renewables, paid for through a surcharge on consumption, creating a reliable market to support higher investment and participation in renewable energy generation. The EEG also prioritizes renewable energy, ensuring access to the grid.
2010	Energy concept	The Energy Concept establishes specific milestones for the integration of renewable energies and climate change mitigation strategies by 2020 and 2050. Targets and methodologies for measuring and assessing energy efficiency are introduced.
2011	Phase-out nuclear power	In response to renewed public opposition following the Fukushima disaster in Japan, the government recommits to closing all German nuclear power plants by 2022.
2014	EEG 2.0	EEG 2.0 reduces fixed tariffs, creating auctions for most solar producers, recalculating the surcharge to assist large industry, and forcing self-suppliers to pay a surcharge.
2016	EEG 3.0	EEG 3.0 suggest that market auctions could soon replace fixed feed-in tariffs for nearly all renewables installations, a 'deployment corridor' would help ensure new capacity growth is compatible with grid expansion, and further liberalization of the auction's markets, including opening up to international producers, might be tested.

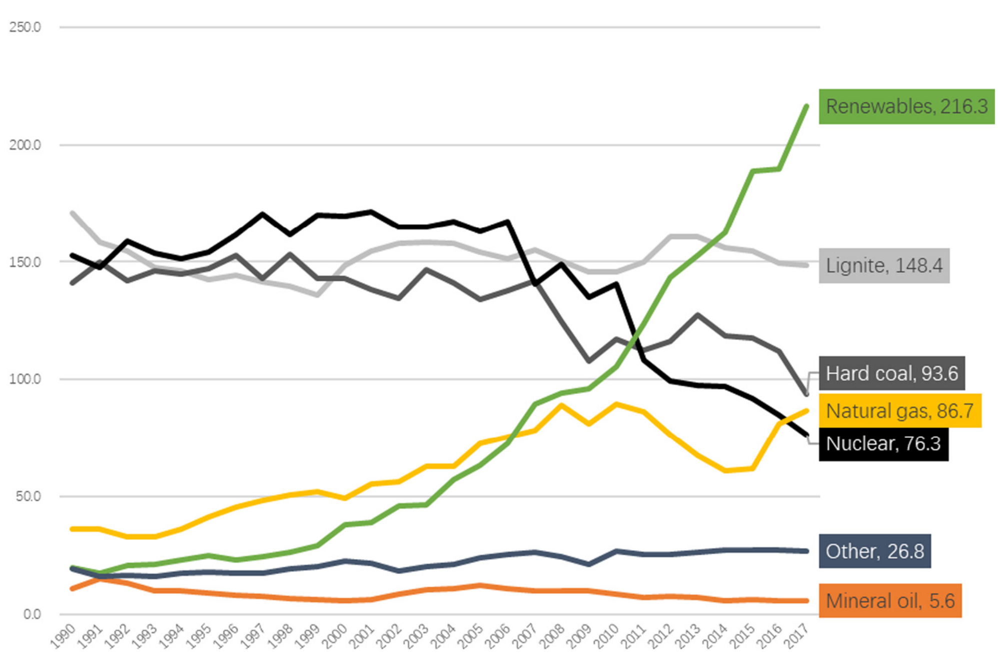

Fig. 1. Gross electricity production by sources in Germany 1990–2017, unit: TWh.
Source: Data source: AGEB (2018).

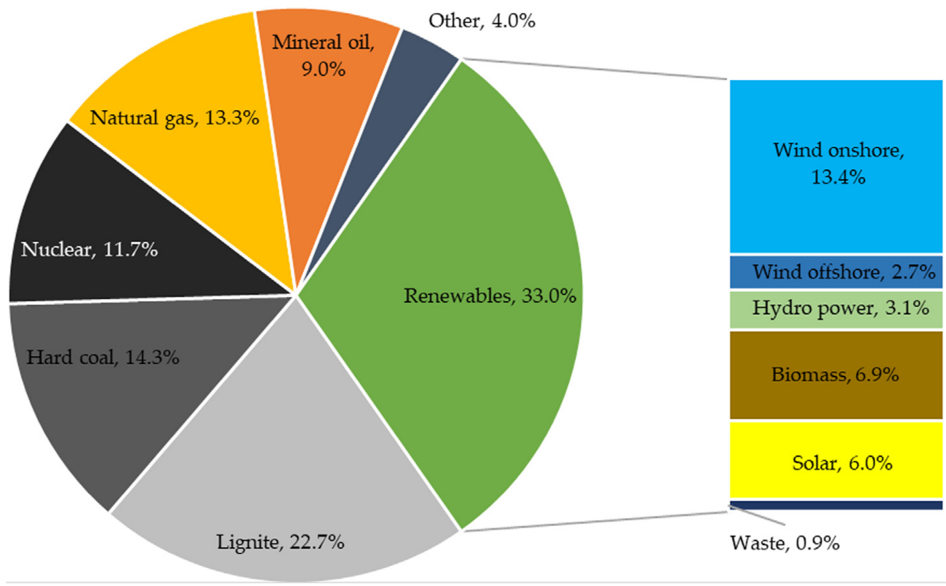

Fig. 2. Share of energy sources in gross electricity production in Germany in 2017.
Source: Data source: BMWi (2018).

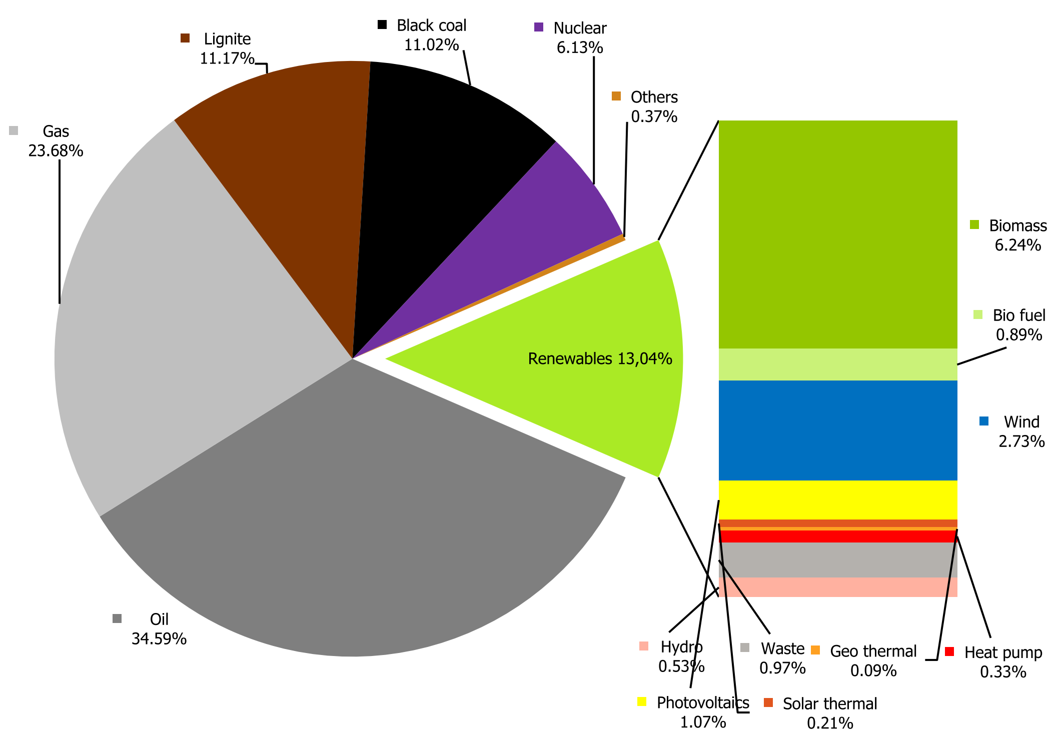

Fig. 3. Primary energy consumption in Germany in 2017.
Source: Data source: BMWi (2018).

While the share of renewables in electricity production has increased greatly, the overall picture is less positive (Fig. 3). In fact, Germany's Energiewende has been about electricity, not energy-transition (Hedberg, 2017). Little has been done to bring about energy transition in the heating and transport sectors. Additionally, its efforts to improve energy efficiency have been insufficient. It has not lowered its dependence on energy imports. It has incentivized the deployment of renewables in less optimal market where the financial return has been weak. As a result, fossil fuels, including coal and gas continue to dominate as the principal sources of energy (Fig. 3). The Climate Protection Report from the government showed that Germany will widely miss its 2020 GHG reduction target by 8% (BMU, 2018).

The price for Germany's energy transition is one of the project's most controversial aspects (Fig. 4). Power prices in Germany are among the highest in Europe (Eurostat, 2017). Despite a slight decrease in early 2018, taxes, levies, and surcharges accounted for more than 55 percent of a total power price of 29.16 eurocents per kilowatt hour (ct/kWh) (Eurostat, 2017). As a consequence, in Germany there is a growing opposition against going forward with the Energiewende (Unnerstall, 2017).

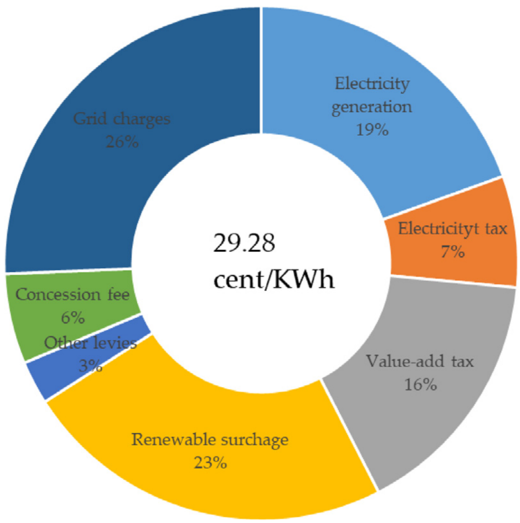

Fig. 4. Component of the German electricity price in 2017.
Source: Date source: BDEW (2018).

2. Energy transition in China

2.1. Background

In 2014, Chinese President Xi Jinping called for an "Energy Revolution", specifying on reducing energy consumption, increasing energy supply, improving energy technology and institutional reform (IEA, 2017). Actually, the idea of "Energy Revolution" was officially introduced by previous President Hu Jintao in 2012 during the 18th national congress of the Communist party of China (CPC), The "Energy Revolution" initiates ecological civilization construction, holding the idea of revolution of energy production and consumption". The transition to a cleaner energy system is driven by the need to improve air quality, combat climate change, and eventually reduce the dependency on fossil fuels. Also, supporting a growing economy and at the same time reducing the carbon foot print are targeted. Additionally, responding to the global efforts towards climate governance, China has, in its nationally determined contribution (NDC) commitment announced on 2016, set its energy-related targets for 2030: peaking CO_2 emissions by 2030 the latest; lowering carbon intensity of GDP by 60%–64% comparing with 2005 levels by 2030; increasing and achieving the share of non-fossil energy consumption among total primary energy consumption to around 20% (NDRC, 2015).

China's overall energy strategy includes several elements. For industrial policy, the Made in China 2025 plan emphasizes green technology such as renewable energy, electric vehicles, and advanced power system equipment. In the near-term, *China National Energy Administration* (NEA) recently issued *Work Guidance of Energy Sector* 2018, also emphasizing shifting towards low-carbon, clean energy and clean heating supply while restricting coal consumption. China has also launched a series of documents on renewable energy development at the city level, for example, 36 low-carbon pilot cities, 81 new energy model cities, and eight new energy industrial parks are selected as demonstration projects (Yuan et al., 2018). The energy transition in a rural area is also happening, for example, from traditional biomass energy to commercial energy like electricity (Han and Wu, 2018) (see Table 3).

2.2. Milestone

The Chinese government has a variety of top economic and social development plans regulating energy production and consumption. Responding to the Five-Year Plan (FYP), China has unveiled its 13th FYP on energy (NDRC, 2017a), which represents the basic outline of China's energy policy from 2016 to 2020. In particular, it sets the first ever mandatory coal cap, and shows the commitment of government to cut coal's share in the country's energy mix, indicating a right track towards its energy transition. FYP for each category such as electricity in general, coal, natural gas, wind power, and solar power have also been sequentially released. For example, the *13th FYP on Renewable Energy* provides specific goals and measures, with a particular focus on renewables for 2016–2020 (NDRC, 2017b). Along with FYPs, the *Strategic Energy Action Plan* (2014–2020) was issued by the State Council in 2014 (State Council, 2015). This strategy plan aims to reduce China's high energy consumption per unit GDP ratio through a set of measures and mandatory targets, promoting a more efficient, self-sufficient, green and innovative energy production and consumption. It puts forward energy conservation as a priority in the power, industrial, building, and transport sectors.

In April 2017, "*Energy Supply and Consumption Revolution Strategy* (2016–2030)" was released (NDRC, 2017c). Beyond the pathway of the 13th FYP on Energy, it set up new and higher targets for future. The main focus of the strategy remains a commitment towards a sustained growth in the utilization of renewables, gas and nuclear power and a radical decrease in the consumption of high-carbon fossil energy. In 2030 primary energy consumption should be controlled within 6 billion tons, and non-fossil fuel in the energy mix should be higher than 20%. Looking into 2050, total energy consumption would stabilize and non-fossil would account for more than half of it. With this Strategy, China is expected to become a major player in global energy governance. In addition, National Action Plan on Climate Change and China's Intended National Determined Contribution have set energy related targets, responding to the global climate change (see Table 4).

2.3. Status quo

China has begun to diversify its energy mix and turn to renewable energy over the past 10 years. From 2005 to 2017, the share of renewable energy generation increased from 16% to 25%. The yearly added wind power installed capacity has declined while solar PV are surging. Based on the results of the China Renewable Energy Outlook 2017 (CNREC, 2017), the annual flagship publication of China National Renewable Energy Centre, the share of wind in total primary energy supply is expected to rise from 0.7% in 2016 to 4% by 2020, 12.5% by 2035 and 21.8% in 2050. Solar PV is expected to rise from 0.3% in 2016 to 1% in 2020, 6.5% in 2035 and 13.4% in 2050

However, fossil fuels still dominate the energy system. The total final energy consumption amounted to around 3,230 Mtce in 2016, with 61% of the energy consumption related to industry, 21% related to transport, and 14% related to buildings. Coal is the dominant fuel in the end-use sectors. In 2016, 39% of the final energy consumption was coal, 27% was oil, 19% electricity, natural gas 7%, district heating 5%, and bioenergy 2% (CNREC, 2017).

Despite a tremendous growth in renewable energy in China recently, the current Chinese energy system is far from the development targets of being clean, efficient, safe, and sustainable. According to the latest information from Chinese Electricity Council, as the largest share of Chinese electricity, thermal accounted for 71%, where coal dominated the component. Nuclear energy remains moderately (4%). Hydro power accounted for the majority of the renewable electricity generation. Wind and solar

Table 3
Targets within China's energy revolution targets.

	Target	2020	2030
Carbon emission	Carbon emission per unit of GDP (compared with 2015)	−18%	
	CO_2 emission		Peak or earlier
	Carbon emission per unit of GDP (compared with 2005)		−60% to-65%
Non-fossil	Non-fossil fuel in the energy mix	15%	20%
	Natural gas in the energy the mix		15%
	Non-fossil power generation account for total power generation		50%
	New energy demand met by clean energy		Should mostly be done
Energy efficiency	Energy consumption per unit of GDP (compared with 2015)	−15%	
	Primary energy consumption (unit: billion tonne tce)	5%	6%
Energy self-sufficiency	Energy self-sufficiency rate	above 80%	
Energy governance	By 2050, China shall become an "important participant" of international energy governance		
Vision towards 2050	By 2050, primary energy consumption should be stable, with more than half coming from non-fossil energy.		

Table 4
Overview of major energy policies and strategies in China.

Year	Document title	Key context
2014	Energy Development Strategy Action Plan (2014–2020)	Reduce China's high energy consumption per unit GDP ratio through a set of measures and mandatory targets,
2014	National Action Plan on Climate Change (2014–2020)	Set energy related targets, responding to the global climate change
2016	13th Five-Year Energy Development Plan (2016–2020)	Set the first mandatory coal cap, and show the commitment of government to cut coal's share in the country's energy mix, indicating a right track towards its energy transition.
2016	13th Renewable Energy Development Plan (2016–2020)	Provide specific goals and measures, with a particular focus on renewables for 2016–2020
2016	Energy Supply and Consumption Revolution	Specify the long-term energy target towards 2030, and even longer, to 2050.

are supported via a feed-in tariff and are becoming increasingly established. However, wind accounted only for 5% and solar for 2% of total electricity generation (China Electricity Council, 2018), as can be inferred from Fig. 5.

2.4. Challenges

While China is undoubtedly committed to a low-carbon energy transition over the long term, there are numerous short-term challenges. Along with the economic development, energy demand continues to grow rapidly but fossil fuels remain essential for meeting present needs.

The institutional reform is a challenging part of the "Energy Revolution". Conflicts between provincial and national objectives need to be addressed urgently. Most provinces have overcapacity of coal power. Provincial officials concern that the reform could threaten the financial viability of province-owned power groups. This means that bilateral contracts, inter-provincial power trades, and spot market pilots should in place to promote economic dispatch. Furthermore, bottom-up policy initiatives and market-based instruments are rare in China. The ongoing power sector reform should solve these issues and create a whole new framework for power system operation and development. However, the implementation of the power market reforms is currently proceeding slowly. Joint plans are missing in different provinces, which often have conflicting interests when it comes to co-operation on market set-up and trading arrangements (CNREC, 2017).

Secondly, China's electricity dispatching and absorption mechanism does not match the speedy development of renewable energy. Due to China's geographical mismatch between resources and load centers, over 70% of China's large-scale wind and solar projects have been installed in the resource-rich northern regions featuring low electricity demand and low export capacity (Zhou and Lu, 2017). However, the construction of inter-regional transmission capacity in China has consistently lagged behind the growth of generation assets. Due to grid bottlenecks and china's guaranteed full load hours for coal-fired power plants policy, curtailment of renewable generation has become significant. In 2016, 17% of China's wind power generation (49.7 terawatt hours) was curtailed (NEA, 2016). That is about 10% of the total electric energy consumption of Germany in comparison. Although the central government has established numerous policies to mandate minimum dispatch hours for wind and solar and for elimination of wind and solar curtailment, the integration of these resources remain a severe problem in several provinces. For example, in northeast Gansu Provinces, large amounts of wind and solar cannot be absorbed by demand inside the province, yet transmission capacity and broader dispatch areas for clean energy have lagged. In order to reform the electricity-dispatching mode, the investment in developing and constructing of energy-friendly grid should be promoted.

Energy efficiency is still left behind in China. As the dominant of coal in the primary energy consumption mix will not fundamentally change in the near future (Zou et al., 2016), it is necessary to reduce direct combustion of bulk coal and strengthen the

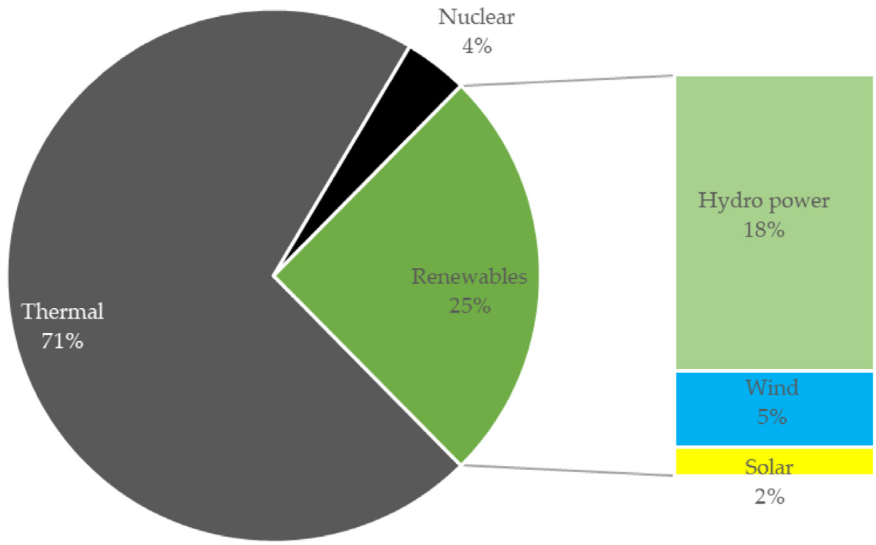

Fig. 5. Share of energy sources in gross electricity production in China in 2017.
Source: Date source: China Electricity Council (2018).

efficient and clean use of coal for purpose of environmental protection. The overall efficiency of China's energy system is still low, compared to economic potential and energy structure. In 2015, the energy consumption per 10,000 RMB of GDP went down by 5.6 per cent. However, the comprehensive energy consumption per ton of steel and per ton of cement only dropped by 0.56 per cent and 0.49 per cent respectively. This suggests that raising the efficiency of heavy industries can hardly further improve the whole energy system efficiency.

3. Comparison and synergies between Germany and China

At the renewable energy sectors, both China and Germany take renewable energies as a key driving force in energy transition. In China, the rise of electricity and renewables are closely interlinked as China diversifies and cleans up its power mix — the share of coal in total generation falls from two-thirds today to less than 40% in 2040 as a result (IEA, 2017), in other words, China sees renewables as a source of energy security and not just only to reduce carbon emission. Currently, China accounts for more than 40% of worldwide renewable capacity growth, and will continue to lead its expansion to another 30% by 2022 (IEA, 2017). Even though the 13th five-year plans renewables capacity targets for 2020 are minimum targets, however, if the scenario of "Below 2 °C" was taken into account, the renewables development should go beyond the current targets: Solar from 110 GW to 200 GW, wind from 210 GW to 350 GW, bioenergy from 15 GW to 30 GW, according to the report of "China Renewable Energy Outlook 2017"(CNREC, 2017). While in Germany, expanding renewable energies has being taken as one of the two fundamental pillars for energy transition. The renewables provide major source for electricity needs of Germany, providing 37.8% of the electricity needs of Germany in 2018, making Germany becoming a world market leader in global wind and photovoltaics market (Laes et al., 2014). Joint Statement by Li Keqiang, Premier of the State Council of the People's Republic of China, and Angela Merkel, Chancellor of the Federal Republic of Germany on 13 June 2016 in Beijing, China, said that "Both sides welcome the innovative cooperation between universities, research institutions and companies from both countries in the field of sustainable energy. Both sides will work to boost cooperation in the fields of improving energy efficiency and expanding renewable energies".

The role of nuclear power is the fundamental difference between Germany and China. China sees nuclear energy as an important source for energy supply. Non-fossil energy rather than renewable energy appears more often in China's energy policy, which considers nuclear energy and renewable energy under the same umbrella. On the contrary, phase-out nuclear energy is a cornerstone of the German energy transition. The wide debate of nuclear power in Germany was triggered by the Chernobyl nuclear accident in 1986. After the Fukushima disaster, a consensus for the need of phase-out nuclear power plants was reached and the last nuclear power plant will be shut down in 2022. China has published the medium and long-term nuclear power developing plan (2005–2020), which seed nuclear as an important source for energy security, electricity supply and environmental protection. Comparing the shares of nuclear in primary energy consumption, Germany (5,92%) clearly tops China (1,58%) in 2016. However, in Germany, both the amount of nuclear consumption and the share of nuclear in primary energy consumption did decrease profoundly, in particular after 2011. In China, the share of installed capacity of nuclear power generation has increased continuously to assure electric energy supply in a growing economy (Table 5). In 2016, the growth of China's nuclear power generation was 9.6 million tones of oil equivalent (mtoe), which was the largest of any country since 2004.

According to IPCC Report, coal is the most carbon intensive fossil fuel and coal-fired electricity must end by 2050 if we want to achieve the emissions reductions needed to limit global warming to 1.5 °C (IPCC, 2018). Coal phase-out implies several interlinked policies, including the shut-down of coal mines, an exit from coal-fired electricity generation and removal of government subsidies to the coal industry. However, coal phase-out raised many concerns over energy security and reliability of electricity supply. Therefore, a gradual and structured plan is needed. China is the single largest coal consumer in the world, and coal represents more than 60 percent of its energy mix. China's government has made recent announcements that could help to limit its coal use. In particular, the Chinese 13th Five-Year Plan includes plans for a cap on coal-based generation at a maximum of 1,100 gigawatts of capacity by 2020. And there have been recent attempts to control unnecessary new investment. In the long run, coal consumption will continue declining, despite the annual and seasonal fluctuations (Qi et al., 2016). However,

Table 5
Development of nuclear power reactors in Germany and China (as of 5th March 2019).

Country	Operable reactors		Under-construction reactors		Reactors planned		Permanent shutdown reactors	
	Number	Net capacity (MW)	Number	Net capacity (MW)	Number	Net capacity (MW)	Number	Net capacity (MW)
Germany	7	9 515	0	0	0	0	29	16,860
China	46	42,800	11	10,982	43	50,900	0	0

coal will be kept as a strategic important component of Chinese energy system.

However, Germany proposed to phase out coal by 2038 in move away from fossil fuels, in facing the fact that the share of coal in electricity generation in Germany is 37 percent. Traditionally, Germany is Europe's top coal-burner. Coal mining, including lignite, has a strong presence in the country. Energy policy in Germany has historically focused on coal, actually subsidized it with several hundred billion. As a fuel source, lignite is very financially attractive. Brown coal still constitutes about a quarter of the country's power production. Coal power plants have decreased production over past years. But most of Germany's coal plants still run throughout the year. Recently, coal was taking a back seat. In January 2019, a government-appointed coal commission suggested to shut down all coal-fired power plants by 2038 and proposed at least 40 billion euros ($45.7 billion) in aid to regions affected by the phase-out. In October 2017, Berlin was the first Bundesland of Germany to pass a coal phase-out law, putting an end to coal heat and power in that region by 2030.

In terms of the self-sufficiency, for export-oriented nations like Germany and China, security of energy supply and affordable energy are very critical tasks for the energy industry. Currently, Germany imports more than 70% of its primary energy consumption. As Germany's imported energy from neighbor countries, the European energy network played an important role in securing the stability. European grids are being extended and Germany's energy transition is supported by the top levels of the European Union. Therefore, the self-sufficiency in Germany is rather under the context of a larger EU framework. Likely, energy security played an important role in the energy transition in China. However, China's energy security strategy particularly prioritizes maximum self-sufficiency and energy independency. Since China was a net import country of crude oil in 1996, energy supply risk aversion has been included in national energy security strategy (Wang et al., 2018). In 2016, the self-sufficiency rate stood at 79%, in which coal is the primary source of the country's energy security. In this case, energy security will be an important challenge to future sustainable development in China and renewable energy development may be valuable to address this issue.

While Germany has targeted both CO_2 emission and GHG emission, CO_2 emission seems to be the main focus in China. China's CO_2 emissions are supposed to peak more than a decade ahead of its Paris Agreement NDC commitment (CAT, 2017), while the total GHG emissions are likely to continue increasing until 2030. Little attention has been given to its non-CO_2 GHG (CH_4, N_2O, HFCs etc.) and no sufficient supportive action is followed (Zhang et al., 2015). Research shows that China's exports industry, which is largely responsible for the high energy intensive products, such as Cement, Plate Glass, Rolled Steel, Copper Products, is emitting GHG at a rate faster than the country's overall emissions rate.

In the decarbonizing the mobility sector, China is ahead of Germany. The public transportation in many major cities have already adopted to the new policies and replaced all buses by electric or hydrogen-based buses. Also, the major share of motor bikes is electric nowadays. Germany set a goal to put 1 million e-cars on the road by 2020 put but right now just (early 2019) about 130'000 cars with batteries are registered, half of them hybrids, i.e. a gasoline engine is the main engine. Reasons for this failure are manifold: high costs, several standards, missing charging points, low range, no business case, no concerted efforts like it seems to be possible in China.

4. Recommendation for cooperation points

For international climate policy and energy transition, a stronger German–Chinese cooperation would be an essential signal to achieve sustainable growth by the utilization of renewables and reducing high-carbon fossil energy consumption. Germany and China could take further leadership in multilateral process, such as the G20. As the pioneers in energy transition, both countries can learn from each other and initiate a global energy transition trend.

Governmental cooperation between the Germany and China in the field of energy policy started in 2006 (BMWi, 2017). In early 2013, the two countries agreed to intensify their collaboration on establishing a sustainable energy supply. In-depth dialogue on lessons learned from the energy transition and approaches to expanding the use of renewable energy and increasing energy efficiency is therefore of interest for both Germany and China. The *Sino-German Energy Partnership* plays a role within China in sharing lessons learned from Germany's energy transition and in raising awareness among Chinese energy sector stakeholders of the challenges involved in the energy transition. Regular working group meetings and high-level bilateral meetings facilitate in-depth political and technical dialogue on the energy transition between German and Chinese decision-makers. An example is the exchange between the German Kopernikus Energy Transition (ENavi) programme and the Chinese Academy of Science including local players.

Energy partnerships and energy dialogues are the main ways the German and Chinese government engaging to share experience and views on energy policy and the energy sector, and to discuss progress on the energy transition (BMWi, 2017). The energy partnership combines high-level government dialogue and expert advice with the involvement of the private sector. Federal Ministry for Economic Affairs and Energy (BMWi), the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) of China agreed on the specific areas they want to focus on. The *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) GmbH is coordinating the energy partnership on behalf of BMWi and has set up an Energy Partnership Secretariat, with contacts in both Beijing and Berlin. The aim is to learn from the experiences and the main focus is on issues like the renewable energy, energy efficiency, grid system, upgrading energy infrastructure, and rules on the electricity and energy market.

In the business sector, cooperation helps German and Chinese companies to enter new markets abroad. Germany benefits from a cheap supply of green energy products from China. There is a great deal of interest from China in Germany's experience with the flexibilization of coal-fired power plants and market-based mechanisms for systems integration. German companies could advertise their products and services in energy efficiency in buildings and industry. However, Germany can learn from China in the transport sector, with regard to the development of electric cars. China has already introduced a quota for electric vehicles and is also considering a ban on combustion engine cars.

The German manufacturers need to adapt in order to survive on China's future automotive market. In addition, collaboration could also leverage green growth opportunities in fast-developing regions in Asia or Africa. Germany and China should intensify cooperation in joint projects in third countries, for instance in the framework of China's Belt and Road Initiative.

Scientific cooperation is another key point. In a transdisciplinary approach including societal and economic factors, research outcomes from the German energy transition programme ENavi (ENavi, 2018), showed great potentials connected to energy transition. Other forecasts show that the national economy will benefit from 2025 on. The energy transition will be the largest modernization and infrastructure project of the next decades and it also triggers technology breakthroughs, which could have a dramatic cost reduction, and sustain the global deployment. An example might be batteries based on abundant, cheap and ecologically friendly materials with high energy storage densities, something that would boost a global energy transition. In China, until now, no comparable project like ENavi exists, therefore, China may need to take the lessons learned from Germany. In order to intensify the scientific dialogue, we called for further research and discussions.

In Germany and China alike, the cities and municipalities are key to a successful transformation of energy systems and implementation of low-carbon development pilots. The success of these programs will crucially depend on positive experience being gained at the local level. Here, emission reduction targets and strategies must be adapted and implemented with the involvement of citizens, companies, initiatives and local institutions. This is the only way to create ownership of the process.

5. Discussion

Germany's Energiewende is considered as one example of how a highly industrialized economy can transition its power system towards a climate-friendly, economically competitive system while ensuring energy security. However, Germany will likely fail on many of its self-imposed energy transition targets, says the German government (BMU, 2018). On the other hand, as the world's most populous nation and second larger economy, China's Energy Revolution, is thought to have the potential to reset the global energy order. Taking into account the lessons from each other, Germany and China may have the chance to tackle the challenges of transition.

Policy instruments have shown to be practicable and effective to steer investments in the right direction and trigger a change in consumer behavior in both countries. Legislating, taxation and feed-in tariff, are widely considered as driving forces by many countries as important approaches to encourage the development of new energy resources (Saidur et al., 2010). In Germany, the EEG along with its guaranteed feed-in-tariffs was the key for rapid growth of renewable power production by guaranteeing reliable investment conditions. This highly successful instrument has been exported into many other countries and regions across the globe. However, the German government currently changes the legislative landscape of the renewable energy market. Feed-in-tariffs are substituted by auctions to gain more political influence on the speed of renewables' expansion and subject them to market forces, with exemptions to small installations. Similarly, China's renewable energy laws and policy system have played a vital role in speeding up the development of renewable energies. However, the energy polices in the two countries are different in terms of operability and practicability. In China, regulations of energy transition are scattered in various policies and laws, ranging from central level and local level laws, general laws and specialized laws. Some of these are considered rather vague and lacking of operability (Liu, 2019). In contrast, the German EEG is very specific and highly operational. EEG usually explains how to apply in specific operations or special circumstances and some disputable issues were clearly set out. For example, EEG has stipulated the grid connection with regarding to what procedures should be taken, by which actor, in what period of time and who should bear the cost. However, the Chinese renewable energy regulations may be too principled and generalized. Therefore, more systematic and efficient laws and policies should be formulated in China.

Stimulating all stakeholders to take actions at different scales is a key task for energy transition. In Germany, more and more actors are producing renewable electricity on a small scale at a local level. There is still a rather centralized policy, but the system is increasingly becoming an intermix of centrally located stabilizing (coal, gas) power plants for the base load and decentralized renewable energy installations. Even municipal level governments produce their own energy and create their own climate policies. China's aim is to develop an increasingly decentralized electricity system as well. For instance, China has already achieved separation between production and transmission. The second stage is to research and develop independent dispatching of electricity from the transmission system. One of the big challenges in China is the power held by actors in the electricity supply chain. There are almost 900 electricity distributors in Germany, creating a competitive environment. However, in China, there is a need to increase the competitiveness of energy producers, electricity distributors, and transmission system operators. It is extremely important to understand the motivations of all the actors along the energy supply chain. The expansion of renewable energy is accompanied by a shift in the ownership structure of electricity production.

With the EU Emissions Trading System (ETS), Europe has had a trading scheme for carbon permits in place for twelve years which includes Germany. From 2011 to 2016, China has launched seven carbon market pilots in Beijing, Tianjin, Shenzhen, Shanghai, Hubei, and Guangdong. So far, allowances in these markets have been allocated mainly through grandfathering and benchmarking, with only small-scale auctions. A national carbon market was officially announced in December 2017, covering the power and heating sectors, which are responsible for a large fraction of coal use. The market will only start official trading in next several years, and the carbon allowance mechanism design will be promoted continuously. Policy-makers hope that carbon prices play a increasingly important role in promoting the low carbon transition (CNREC, 2018).

Is nuclear power a component of energy transition? Clearly, Germany and China have different answers. In Germany, due to the shut-down of nuclear plants, coal power plants (with much higher emissions) have to make up for it and replace that missing electric energy generation. As a result, despite an increasing share of renewable energy sources, the GHG emissions in Germany are rising. How to meet the transition-paradox and other skeptical critics, Germany and China may need join their forces to find the solution.

The German citizens are the key actors in the voice of phase-out nuclear power. As they attended anti-nuclear power demonstration, promoted environmental organizations and voted for politicians and parties, the politician must hear. In principle, the energy transition continued strong support among the German population. The highest degree of acceptance was shown in Germany, that 93 percent are in favor of further expansion of renewable energies. However, this overall socio-political acceptance needs to be translated into an increasing market-related acceptance which manifests itself in benefits for the people and a more intensive market penetration. While Germany enjoys the support of the public to phase-out nuclear, the decision-making process is more likely to be influenced by politics and experts in China. Although both countries have very different choices on energy transition, it is too far to make a conclusion. Therefore, the channels of cooperations and communications in both countries should be always opened.

6. Conclusion

Energy transition has been a long-term strategy for both Germany and China. After the US decided to step away from the Paris Agreement, Germany and China are expected to take the lead on the global effort to achieve clean energy and GHG emissions reduction. As Chinese Premier Li Keqiang and German Chancellor Angela Merkel agreed to emphasize innovation cooperation in 2014, China and Germany will work together to deepen energy-dialogues. Based on the comparative and qualitative analysis, the background, milestones, current situation and challenges of energy transition in the two countries are reviewed. We found that infrastructure, policy instruments and market reform played the key roles in the transition process in Germany and China. Under the back ground of energy and environmental crisis, the development of renewable energy (such as wave energy, offshore wind energy and so on) is a good strategy. While nuclear power and coal are likely to be abandoned in Germany, China has more ambition beyond the power sector and to reach self-sufficiency. The two countries chosen different concepts and pathways to achieve their transition goals. However, we have now learned that no one can reach its goals independently and they should invest in cooperation. Under the context that Germany and China are acting more ambitiously on the leadership of climate protection and energy transition in international level, the collaboration between each other could not only benefit Germany and China but also leverage green energy growth opportunities in third countries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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