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China's route to carbon neutrality: Perspectives and the role of renewables

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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

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ABBREVIATIONS

°C	degrees Celsius
BECCU/S	bioenergy with carbon capture and utilisation/storage
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
DACCS	direct air carbon capture and storage
EJ	exajoule
EU	European Union
GDP	gross domestic product
Gt	gigatonne
GW	gigawatt
IRENA	International Renewable Energy Agency
kWh	kilowatt hour
LNG	liquefied natural gas
LTES	Long-Term Energy Scenario
Mt	million tonnes
MWh	megawatt hour
PV	photovoltaic
RD&D	research, development and deployment
SEGSN	State Grid's Smart EV-to-Grid Service Network
SGERI	China State Grid Energy Institute
TWh	terawatt hour
WETO	World Energy Transitions Outlook

EXECUTIVE SUMMARY

In September 2020, Chinese President Xi Jinping announced at the 75th Session of the United Nations General Assembly that China would aim for a peak in its carbon dioxide (CO_2) emissions before 2030 and to achieve carbon neutrality by 2060. The implications of these announcements will be profound and will require changes in almost every aspect of how the country consumes energy and produces goods. Forty years is a short period to complete such a major transformation, and although many building blocks exist, many of the details of how to deliver such a change remain unclear. Substantial analysis, careful planning and co-ordinated effort will be needed in the next few years to shape the path to 2060.

China's scale and the need to balance economic development with emission reductions present a challenge in its transition to net zero. Over the past decade, the country has been top ranked in global energy production and consumption. China's energy-related CO_2 emissions have been trending upward to reach 28% of the global total in 2019, according to emission data from the International Energy Agency. At the same time, China has been a key driver of the growth in renewable energy generation capacity, accounting for 34-53% of the global annual growth over the period 2013 to 2021 (IRENA, 2022a).

Although the share of coal in China's energy mix declined around 10% between 2012 and 2019, coal remains the dominant source of primary energy in the country (State Council Information Office, 2020). Therefore, China must scale back its coal use while accelerating the scale-up of renewables. Additionally, reducing emissions from hard-to-abate sectors such as iron and steel making, cement and petrochemicals – which are often energy and carbon intensive – is a particular challenge because of the importance of these sectors to total economic activity.

To meet its carbon peaking and carbon neutrality goals, China will have to maximise the deployment and use of renewables-based power generation. This needs to be combined with direct and indirect electrification of end-use sectors (building, industry and transport), which needs to be supplemented with sustainable use of bioenergy, hydrogen and synthetic fuels. Doing so will require a fundamental rethinking of traditional concepts of energy supply and security and should accelerate the pace of generating and disseminating the systemic innovations needed to drive the energy transition process (IRENA, 2019a).

China is not alone in this journey. Other countries are also undergoing this transition and making efforts to advance and deploy the technologies that will be needed to realise it. China could both contribute to and benefit from international co-operation. Exchanges of experience gained and lessons learnt at the domestic and international levels can facilitate the development of viable transition strategies.

IRENA's technology-focused analysis

This paper provides some initial insights based on the technology-focused work of the International Renewable Energy Agency (IRENA) with countries around the world, as well as on IRENA analysis of global and regional energy transitions. The paper draws on multiple IRENA reports on power sector flexibility, hydrogen and the sustainable use of biomass. It also draws specifically on IRENA's *Innovation Landscape for a Renewable-Powered Future* report (IRENA, 2019a) and supporting briefs, on the *Reaching Zero with Renewables* report (IRENA, 2020a) and on IRENA's global roadmap – the *World Energy Transitions Outlook* (WETO) (IRENA, 2021a; IRENA, 2022b) – which is focused on a scenario consistent with limiting global temperature rise to below 1.5 degrees Celsius (°C), by eliminating global CO_2 emissions between now and 2050.

This paper summarises key insights from these and other analytical reports and explores their relevance to China's specific context. The paper aims to support learning from global experiences, prompt discussions and inform the further work needed to chart the path to carbon neutrality in China by 2060.

Areas for action and recommendations

As a starting point for discussions and to identify priorities for deeper analysis, this paper identifies 13 priorities for stronger action, together with recommendations:

1. Developing and delivering an integrated long-term energy plan

Effective and integrated energy planning is fundamental for a successful energy transition and can deliver the enabling conditions that the energy transition would require.

The energy transition is not something that can be accomplished by a single governmental body. Multiple institutions must work together. In the context of the net zero goal and building on good practice in China to date, further co-ordination is needed to establish a strong governance structure, not only between energy planning agencies and institutions but also between the energy and climate communities. China has a strong track record of effective development and implementation of Five-Year Plans. In recent years, long-term perspectives and guidelines provided by top policy makers give context and provide strategic policy objectives. These need to be operationalised further.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Co-develop scenario-based long-term strategies and plans for carbon neutrality by 2060, including at the national and the sub-regional/provincial levels and by sector.**
- **Utilise global best practice for long-term scenario development, drawing on experience and best practices from around the world through IRENA's Long-Term Energy Scenarios Network.**

2. Maintaining energy efficiency improvements as a priority

Maximising energy and resource efficiency and minimising the energy and resource intensity of economic activities is usually the most cost-effective strategy to reduce energy consumption as well as emissions. Significant potential exists for efficiency improvements in China in many areas, and synergies remain to be exploited between increased electrification of end-use sectors and improved efficiency of energy service supply.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Maintain a strategic focus on maximising energy and resource efficiency and minimising the energy and resource intensity of economic activities.**
- **Exploit additional opportunities for improvements, including accelerating the growth of the service sector, promoting a circular economy and utilising digital technology.**

3. Accelerating the phase-down of coal consumption

To achieve emission peaking before 2030 and net zero by 2060, the total consumption of fossil fuels must be capped and subsequently reduced, while the phase-down of coal for power generation is a priority. The principal barriers are primarily not technological (renewable power technologies constitute a proven alternative today) or economic (renewable power is cheaper than alternatives in most circumstances).

Today's barriers are mostly related to changes in policies and legislation. In some cases, local socio-economic considerations play a role, with some regional jobs and local economies being heavily dependent on fossil fuels (in the Chinese case, predominantly on coal). Addressing these barriers will require clear political direction coupled with careful transition planning to mitigate socio-economic impacts that may arise due to transformation of the current energy systems.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Progressively strengthen China's national emissions trading scheme to ramp up carbon emission reductions from the most emitting plants, notably coal-fired power plants.**
- **Reduce coal consumption further during the period of the 15th Five-Year Energy Plan, which would be an important signal for the long-term transition away from coal.**
- **Draw on a growing body of evidence and experience internationally, through co-operation and dialogue, to enable China to make well-informed decisions on how to develop economic transition strategies for coal-reliant regions with as few adverse impacts as possible on local economies.**

4. Accelerating the transition towards renewable power

Globally there is a need to triple the power supply by 2050 from the current level, as the role of electrification and the use of electrofuels (e-fuels) rises. Cost reductions mean that renewables are now the sensible economic supply choice. Globally 75% of onshore wind and 40% of utility-scale solar PV produced electricity is at present cheaper than fossil fuel-based alternatives. Renewables should therefore be the preferred route for power generation, and solar power, wind power and hydropower should become the backbone of China's power supply in the future. Renewables can potentially meet more than 90% of Chinese power demand by 2050, with a solar and wind energy share of over 60% (IRENA, 2020b).

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Exploit China's strengths and experience with renewables to accelerate deployment. China now has the capacity and experience to step up the deployment rate at an even faster pace.**

- **Stimulate the development and uptake of emerging renewable energy technologies such as offshore wind, which could play a significant role. Offshore wind farms located close to load centres along China's eastern coast reduce the need for long-haul transmission from remote western regions.**

5. Reforming power networks

The variability of wind and solar power can pose challenges for safe and stable operation of the power system, but a growing range of solutions exist to counter that by enhancing the flexibility of energy systems.

Globally the renewable energy share in total power generation should reach 90% by 2050, and nearly three-quarters of the total installed capacity and more than 63% of all power generation should come from variable renewable energy resources, up from around 20% of the installed capacity and nearly 10% of power generation globally today (IRENA, 2021a). China needs to consider how to transition its power systems to a hybrid configuration that combines both centralised and distributed power generation systems. China also needs a more flexible inter-regional electricity market to sustain the transition.

Such changes can be enabled by the adoption of systemic innovations – an approach to facilitate the diffusion of innovative technologies with improved enabling environments such as business models, market structure, new regulations and overall system operations. Thus, the flexibility in energy systems could be improved and more variable renewable energy can be integrated in the power mix.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Continue to promote power market reform to incentivise a flexible energy and electricity market. This will in turn accelerate the upgrading of electricity infrastructure – including the integration of smart grids, energy storage, distributed systems and other digital technologies – and also facilitate inter-regional power exchange.**

- **Stimulate investment in ultra-high-voltage transmission between the regional power markets. Given that a large amount of China's renewable energy resources are in the western and northern regions, such investment remains important despite scaling up the use of local renewables in the eastern and central regions.**

6. Increasing the electrification of end-use sectors

It is increasingly clear that electrification of the transport, industry and buildings sectors should be given serious consideration as a promising option for reducing end-use emissions, given the rapid deployment of renewable power generation capacity. Dramatic reductions in the cost of renewable electricity open up new cost-effective options to substantially reduce end-use energy demand, should direct electrification be adopted (IRENA, 2022c). In China, the combination of electrification and renewables is already starting to transform sectors such as light-duty road transport and buildings. Electrification will also have a role in industry and long-haul transport.

While increasing the pace of electrification will be critical, it will be important to avoid un-co-ordinated electrification, which could threaten to increase system peaks and cause issues for transmission and distribution networks. Smart electrification enabled by good planning and digitalisation will be a necessity to reduce peak loads, thus reducing the need for investments in enhancing the grid operation or adding new generation capacities.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Develop a long-term vision of the role of electricity in the country's energy system, including engaging multiple stakeholders and expanding smart electrification infrastructure, such as transmission and distribution grids, decentralised systems, smart charging networks for electric vehicles, and district heating and cooling systems as well as integrating facilities for green hydrogen production and distribution.**

- **Modernise electricity grids, particularly through accelerated deployment of digital grid technologies and solutions, enhanced integration of various end-use sectors and increased large-scale energy storage capacity. This will be critical for implementing the electrification strategy.**

- **Relocate the production facilities of some energy-intensive industries to the western and northern regions of China to take advantage of abundant renewable electricity there, provided that other critical factors for such re-allocation (such as land, labour forces and availability of other resources for industrial production) would allow this.**

- **Adapt regulations to better reflect inter-relations among sectors, especially in cities, for example by further promoting price reforms, removing barriers to adopting innovative technologies, and incentivising widespread adoption of heat pumps, smart meters and other smart electric appliances.**

7. Expanding the direct use of renewables, particularly biomass for energy purposes

Solar thermal, bioenergy and geothermal will be further needed at greater scale to provide zero-carbon thermal energy for space heating and cooling (absorption chillers) and hot water in buildings, as well as for industrial processes, through direct use of the resources. In addition to direct use, biomass can be used as a feedstock for alternative materials to fossil fuels, both as inputs in industrial processes as well as in the production of transport fuels such as biofuels.

Given the wide range of applications, bioenergy accounts for the bulk of global renewable energy use and for 10% of global total final energy consumption. However, the contribution of modern bioenergy remains small – only 1.5%. Nevertheless, it is expected to grow to 17% of global final energy demand by 2050 (IRENA, 2021a). IRENA's analysis suggests that the demand for biomass as a feedstock for energy use to deliver net zero by 2050 can be met without adverse impacts on forestry and other land-use purposes, if effective measures in regulation, certification and monitoring are taken.

In China, bioenergy has been developed and deployed at a much slower rate compared to solar PV and wind power over the past decade. The challenges lie in the limited resources rather than in the many competing interests for use, as well as in the sustainability of bioenergy feedstock provision. Effective approaches and strategies would be required to ensure that the feedstocks are exploited sustainably and are ecologically friendly, and that the resources to be used are those that can add the most value – such as for biojet fuels to decarbonise the aviation sector, an area where China would need to catch up in technologies and production capacities.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Fully integrate the use of biomass in both the energy sector and other end-use sectors, in particular by establishing cross-sectoral co-ordination mechanisms among energy, agriculture and forestry policy makers.**
- **Achieve greater value for various end users of biomass through biorefineries.**
- **Explore the potential adoption of innovative technologies associated with the use of biomass, such as bioenergy with CO_2 capture and utilisation/storage (BECCU/S), a promising technology for decarbonisation while absorbing carbon that is already in the atmosphere. Many more pilot projects are needed, alongside mechanisms to share learning.**

8. Scaling up the production and use of hydrogen and synthetic fuels

Hydrogen has several attractive features for the energy transition. It can offer a solution for types of energy demand that are hard to electrify directly. At the global level, hydrogen and the direct use of renewables can meet around 50% of the final energy uses that may not be suitable for direct electrification. Transport of hydrogen through pipelines would be much more cost efficient in comparison with electricity transmission over power grid networks per unit of energy. In addition, hydrogen produced from renewable electricity via the electrolysis process can contribute to the integration of more variable renewable energy in the power sector by providing an additional source of flexibility, and can also provide seasonal storage complementing short-term storage (*e.g.* batteries).

Globally hydrogen and its derivatives could meet 12% of final energy use in the coming three decades or so, with two-thirds of this being green hydrogen, according to IRENA's analysis (IRENA, 2022b). To make this happen, production of green hydrogen would need to scale up rapidly to achieve economies of scale that would allow it to become cost competitive with blue hydrogen by the end of the 2020s in many countries and regions.

There is substantial scope to scale up green hydrogen production in China, although it will be important to ensure that any renewable capacity used for hydrogen is additional to the planned activities and that hydrogen is not displacing more efficient uses of electricity (*i.e.* direct use).

China has two key advantages with hydrogen. First, relatively lower labour costs and industrial development compared to other countries would contribute to continued declines in the production costs of electrolysers. Second, the demand for green hydrogen in China can provide the opportunity to scale up global deployment of the production capacity, facilitating the shift from fossil-based to renewables-based hydrogen production, and can lead to learning effects and cost declines.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Develop a supportive policy framework that encourages fuel shifts in industry, and expand the scope of eligible fuels to hydrogen and its derivatives.**
- **Demonstrate and build experience on hydrogen end-use applications, including road transport with hydrogen fuel cells, alternative reduction agents to coke coal in the iron and steel industry, ammonia for shipping and synthetic fuels for aviation. China could attain global leadership in these technologies, if greater efforts can be made to support the technological innovations needed to overcome the current under-performance of Chinese electrolysers (Heyward, 2022).**
- **Support the domestic electrolyser industry to enable growth, learning and competition leading to technological leadership for China.**

9. Supporting cities as champions of low-carbon living

Over the past few decades, China has urbanised dramatically and in an impressive manner given the size of its population. City dwellers now make up 60% of the population, which creates challenges for energy supply and use (CNBS, 2021). Industry accounted for around 71% of the country's urban final energy consumption in 2018, while buildings accounted for around 19% and transport for 10% (SGCERI, 2019).

Cities are diverse, and there are no one-size-fits-all solutions. The urban energy infrastructure of the future will be shaped by today's investment decisions and urban planning. Sustainable solutions must be identified from a long-term, system-wide perspective to avoid the creation of stranded assets. An effective analysis framework to identify solutions for cities should include bottom-up planning elements that reconcile with the long-term, low-carbon urban and regional energy strategies.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Encourage local authorities to develop long-term integrated urban planning, with the twin aims of achieving carbon neutrality and better liveability.**
- **Prioritise distributed energy generation to maximise the use of local renewable energy resources, coupling end-use sectors and urban infrastructure, using digitalised intelligent energy management systems and improving energy efficiency.**

- **Contribute to energy system flexibility by making urban energy demand more responsive to the generation from variable renewable electricity from the national grid.**

- **Reform urban waste use to incentivise recycling and appropriate disposal, including through a properly designed waste management system.**

10. Continuing progress in light-duty transport and broadening to heavy-duty and long-haul modes

Falling costs and rising shares of renewable energy in China's power mix open the door for transforming the transport sector so it is mostly centred around direct and indirect electrification. The technological options that can accelerate such a transformation include the direct use of clean, preferably renewable, electricity (for rail and road transport, including heavy-duty road freight transport); the use of green or blue e-fuels, such as hydrogen, ammonia and other e-fuels (particularly for shipping and some heavy-duty road freight transport); and the use of biofuels (particularly for aviation). Among these options, electrification of transport is generally viewed as the most promising, particularly for light vehicles, thanks to the continued decline in the generation cost of electricity from renewable energy sources.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

For domestic transport:

- **Continue the roll-out of electric vehicles and charging infrastructure. This includes ensuring that charging infrastructure is "smart", creating incentives for low-carbon road freight deliveries and developing integrated roadmaps for transport sectors.**

- **Exploit possible shared impetus from other sectors, such as: incentives for lowering the cost of batteries that would benefit more than just the transport sector; the increased demand for cost-competitive green hydrogen and the established supply chain for green hydrogen use; and the supply of sustainable sources of feedstocks for biofuels.**

For international aviation and shipping:

- **Build on the overall effort to reduce carbon emissions in China to develop a carbon neutrality strategy for the aviation sector, and incentivise the adoption of low-carbon flight options.**

- **Conduct more detailed studies on the realistic potentials of key alternative aviation fuels (*i.e.* biojet and synthetic fuels).**

11. Laying the groundwork for industrial sectors to achieve net zero emissions

How to achieve net zero emissions in the industrial sectors is a global challenge that has barely begun to be tackled. This is because it will require fundamental changes in the production, consumption, and recycling and disposal of products, and industrial sectors are diverse. China is the world's largest producer of several key energy-intensive commodities, so its actions and leadership will be critical.

For industrial sectors, the 2020s need to be a decade of preparation, laying the groundwork for major shifts in production processes and very deep emission cuts in the subsequent decades. Actions in the 2020s need to focus on creating and proving the solutions needed and establishing the enabling conditions. Priorities for action include: providing clear signals from government; learning what works by establishing many more demonstration plants; and beginning to address essential enabling conditions including financing, fuel and feedstock supply infrastructure, standards and certification, and trade conditions.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Set a clear direction by co-developing with industry and other stakeholders low-carbon strategies and roadmaps for each sector.**
- **Reduce energy use through energy and resource efficiency and demand reduction.**
- **Transition away from coal use in industry and build knowledge on the use of renewables.**
- **Explore the optimal locations for industrial production, including relocating to regions that have abundant renewable energy resources but low existing demand for electricity, provided that other critical factors for production can also be met.**

12. Continuing to support technology RD&D and broader systemic innovation

Since 2013, China has increased its investment in clean energy research, development and deployment (RD&D) and has become the second largest public sector investor behind the United States (although the European Union [EU] and its members collectively invest more). However, nearly half of the Chinese energy RD&D budget was spent on technologies that are not consistent with the country's carbon peaking and neutrality goals. By contrast, 97% of the energy RD&D budget in the EU was focused on clean energy RD&D in 2019.

This imbalance needs to be addressed if China wishes to deliver its objectives and play a leading role in clean energy technologies. Support for technology RD&D also needs to be linked to broader systemic innovation – that is, combining innovation in enabling technologies with innovative business models and with innovations in market design and energy system operations.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Increase public sector investment in clean energy RD&D.**
- **Adopt a systemic approach to innovation.**
- **Expand China's leadership role in international RD&D collaboration.**

13. Deepening global engagement

The energy transition is a global effort requiring greater international co-operation. Learning best practices from other countries or regions can benefit China, and Chinese expertise can help shape global markets. International organisations can support that mutual co-operation and learning.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

- **Be a visible leader in global energy and climate governance and strengthen participation in global and regional co-operation mechanisms and international bodies.**
- **Showcase China's successes as a major provider of a full range of system solutions for carbon neutrality.**

CHAPTER 1
CHINA'S CARBON DIOXIDE EMISSION GOALS IN THE GLOBAL CONTEXT

At the 75th Session of the United Nations General Assembly in 2020, China announced that it aimed to achieve a peak in its carbon dioxide (CO_2) emissions before 2030, and to achieve carbon neutrality by 2060. In December 2020, China further detailed that, as part of its Nationally Determined Contribution under the Paris Agreement, it aimed to reduce the carbon intensity of its gross domestic product (GDP) more than 65% by 2030, while increasing the share of non-fossil fuels in primary energy consumption to around 25% and the forest stock volume by 6 billion cubic metres, from 2005 levels respectively. In addition, China will scale up its total installed power generation capacity from solar and wind to more than 1200 gigawatts (GW).

The implications of these announcements will be profound and will require changes in almost every aspect of how the country consumes energy and produces goods. Forty years is a short period to complete such a major transformation, and while many building blocks exist, many of the details of how to deliver such a change remain unclear. Substantial analysis and co-ordinated effort will be needed in the next few years to shape the path to 2060.

For the first time, China has developed and issued a dedicated five-year plan on addressing climate change, in addition to an energy development plan. Effectively implementing these plans with province-level actions will be crucial for China to be on track towards achieving its 2060 carbon neutrality goal.

1.1 Global context

Many major economies – including all members of the Group of Seven (G7) plus the European Union (EU) – have made political or policy commitments to achieving net zero CO_2 emissions by mid-century. The EU has legislated for a goal of net zero by 2050, and five European countries (Denmark, France, Germany, Hungary, Luxembourg, Spain, Sweden and the United Kingdom) have already passed national legislation, while more countries have declared net zero policy goals. Notably, as part of its net zero plans, the EU has adopted a new Carbon Border Adjustment Mechanism, which has big implications for global markets.

In North America, Canada is in the final stages of enacting legislation targeting net zero by 2050, and the Biden administration in the United States has declared a similar goal. In Central and South America, Chile is in the process of legislating, while Argentina, Brazil and Costa Rica have declared net zero policy goals.

In the Asia Pacific region, alongside China, both Japan and the Republic of Korea have declared net zero targets, while New Zealand has legislated targets and Fiji and the Solomon Islands are in the process of doing so.

In Africa and the Middle East, there is a pressing focus on ensuring secure and affordable access to energy. At present, only Nigeria and South Africa have declared net zero goals, but in the region and beyond examples are emerging of long-term plans consistent with net zero goals. The growing contingent of countries with net zero goals makes it clear that net zero ambitions now have broad support and that the effort to deliver them can be shared around the world.

1.2 China's unique characteristics

China has a number of characteristics that make its transition to net zero emissions unique. These include:

- China is the world's largest producer and consumer of energy and is also the world's largest emitter of CO_2, accounting for 28% of global greenhouse gas emissions. China's per capita emissions (around 7 tonnes per capita per year) exceed those of the United States (World Bank, 2021a).

- China's economy will need to continue to grow significantly to meet its development objectives. In most developed countries, energy consumption has stabilised as these countries transition to a post-industrial, service-based economy. China would need to double the size of its economy and its GDP per capita by 2035 to achieve its mid-term development objectives. Energy consumption in China is expected to continue to rise for many years to come as the economy develops (World Bank, 2021b).

- China's main energy source is coal, accounting for 56% of primary energy use in 2021, while shares of oil and natural gas in the mix were 18.5% and 9%, respectively (CNBS, 2022). China had 1297 GW of coal-powered generation capacity in 2021, representing more than half of the national total power generation capacity (NEA, 2022).

- China has been a global leader in deploying renewables for nearly a decade. In 2021, it contributed nearly half of the global renewable energy capacity additions, with 134 GW. China's total installed renewable power generation capacity was 1063 GW in 2021, representing 44.8% of the country's total power generation capacity. China generated 2480 terawatt hours (TWh) of renewable electricity that year, or 29.8% of the country's total electricity generation (Government of China, 2022). China has updated its mid-term carbon reduction target by increasing the share of non-fossil fuels in primary energy consumption to 25% by 2030 (from the original 20%) – this represents an increase of nearly 10 percentage points from 2020 levels. The combined installed power generation capacity of solar photovoltaics (PV) and wind turbines will exceed 1200 GW by 2030, up 44% from the 2020 level.

- China has huge regional variation in both its energy resources and energy demand. It has been taking steps to tackle this, for example building long-distance electricity transmission lines to meet increasing power demand in the eastern and central industrial provinces. Since 2019, China has built an ultra-high voltage (± 1100 kilovolt) direct current transmission line to transmit 66 billion kilowatt hours (kWh) of electricity a year from the western to eastern provinces to utilise enormous wind and solar generation (Bloomberg, 2019). However, regional differences in energy supply and demand remain challenging.

- China's urbanisation level has reached around 60%. Urbanisation growth is expected to continue in the coming decades (State Council, 2020), reaching a 65% share under the 14th Five-Year Plan. China's future cities will increasingly develop in the direction of metropolitan circles and urban agglomerations.

- China is currently an export-oriented economy, where the production of energy-intensive commodities far exceeds national consumption. In the context of domestic reform, development, and stability goals as well as global economic challenges, especially the COVID-19 experience, China is proposing to shift that balance by adopting the concept of "dual circulation", whereby the country would rely more heavily on domestic demand (internal circulation) to drive growth but supported by international trade and foreign investment (external circulation) (Olsson, 2021). However, while China is transitioning to that new model, exports will remain an important component of the economy for the foreseeable future. The emission reduction goals of China's export partners, and the carbon intensity-related import restrictions that they may impose, are therefore also relevant to China.

- China holds the largest national production capacity for several key energy-intensive commodities, such as steel, aluminium, cement, plastics, methanol and ammonia; for many of these commodities, China accounts for more than half of total global production. The energy consumption of these industries accounts for around 60% of the country's gross final energy use. Coal has been widely used in the industrial sector, and its consumption has been rising in recent years. This is particularly the case for China's rapidly developing chemical and petrochemical industry: in 2019, coal consumption in China's metallurgical sector grew 7% and in the chemicals sector grew 11% (Hove, 2020).

CHAPTER 2
SHAPING A STRATEGY FOR THE 2020s AND BEYOND

China has set a clear goal for its carbon emissions to peak before 2030. However, bringing forward the timeline to 2025 would greatly assist with the country's subsequent trajectory to net zero, making later implementation plans more manageable. It is critical to use the 2020s as a decade of planning, preparation and learning to gather evidence, make choices and address the enabling conditions necessary to put China on the path to a new modern energy system. Doing so will require a fundamental rethinking of traditional concepts of energy supply and security and should draw on the lessons from domestic energy system development to date as well as on international experiences with energy transition.

The International Renewable Energy Agency (IRENA) is working closely with multiple governments as they begin to develop carbon neutrality plans. While all countries are still in the early learning stages, some common elements are emerging that, with some adaptation to local circumstances, are of relevance to China.

In particular, IRENA, in partnership with many countries and regions, is developing roadmaps for their energy transitions and publishes an annual global roadmap. The 2021 edition of IRENA's global roadmap, the *World Energy Transitions Outlook* (WETO), is focused on a scenario consistent with keeping global temperature rise to below 1.5 degrees Celsius (°C). This "1.5°C Scenario" provides an ambitious energy transition pathway driven mostly by renewable energy sources, electrification measures and continued improvements in energy efficiency. This would enable the world's energy system to transition towards net zero carbon emissions by 2050.

The second edition of the WETO, launched in March 2022 at the Berlin Energy Transition Dialogue, outlines priority areas and actions that can and must be implemented by adopting and scaling up the existing technologies in order for the world to achieve net zero emissions by mid-century.

Drawing on the key insights from these publications and on relevant ongoing work on the technology-driven aspects of energy transitions around the world, which are of strong relevance to China, the following 13 priority areas for concerted Chinese action are put forth.

2.1 Developing and delivering an integrated long-term energy plan

Effective and integrated energy planning is fundamental for a successful energy transition. Long-term energy scenarios are a powerful tool for planning and policy making, which can provide a strategic framework guiding the development of both China's Five-Year Energy Plans and longer-term strategies. Energy planning and policy issues are different for the short, medium, and long terms, but near-term plans must be aligned with the long-term strategy.

A 10-year time horizon to 2030 (by when China aims to peak its emissions), for example, needs to capture structural change and the deployment of emerging technologies, as well as system inertia that results from existing capital stock. However, a 2050 or 2060 time horizon (by when China aims to reach net zero emissions) needs to explore innovations and normative long-term policy objectives, such as deep decarbonisation.

China could both contribute to and learn from the growing body of global expertise on energy transition planning. In this context, IRENA's Long-Term Energy Scenarios (LTES) Network[1] provides a platform for national and regional practitioners to share their experiences and good practices in the use and development of long-term energy scenarios to guide the energy transition. The LTES Network currently gathers more than 22 countries and 7 technical institutions, including China's State Grid Energy Research Institute (SGERI).

Discussions within the LTES Network show that, often, the development of various plausible scenarios needs to involve a range of national institutions during different stages. In China, SGERI takes the scenario development approach to plan China´s large-scale energy base, as well as capacity expansions of cross-regional transmission lines. Additionally, LTES are used as recommendations for policy measures on how to reach China's targets as laid out in the Five-Year Plans.

In the context of China's new net zero goal and building on good practice in the country to date, further co-ordination is needed to establish a strong governance structure, not only between energy planning authorities and institutions but also with the climate community. Complementing and building on the 14th Five-Year Energy Plan, and on the 15-year mid-term vision, a long-term roadmap for the transition between now and 2060 can guide the activities of multiple stakeholders and reconcile the short- and long-term objectives of China.

Delivering an agreed plan will require collaboration beyond traditional boundaries to marshal the expertise and efforts of a diverse range of actors – including the Chinese government, energy companies and leading institutions (both internal and external) – as well as strong international collaboration. Delivering the enabling conditions for the energy transition would require the relevant institutions to work together, and their goals must be well co-ordinated. National ministries will need to work closely with each other and secure the active support of provincial administrations. It is particularly critical to find economically viable alternative solutions, particularly for provinces that are economically dependent on coal.

[1] *For more information, please visit www.irena.org/energytransition/Energy-Transition-Scenarios-Network/ETS-Net-Events.*

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Complement the Five-Year Plans and the 15-year mid-term vision, by co-developing scenario-based long-term strategies and plans**
   China should complement the Five-Year Plans and the 15-year mid-term vision, with scenario-based long-term strategies and plans for achieving carbon neutrality by 2060 at the sub-regional/provincial level and by sector. Such plans will help align the work of many actors involved in China's energy transition. The development should involve a broad range of key stakeholders across central government, the provinces, cities and towns, and others and should bring together energy and climate policy more closely.

2. **Utilise global good practice for long-term scenario development**
   China should continue to refine its long-term energy scenarios, drawing on experience and best practice from around the world. IRENA's Long-Term Energy Scenarios Network offers a global platform to share the Chinese experience in long-term scenarios and their use for guiding the clean energy transition.

2.2 Maintaining energy efficiency improvements as a priority

Maximising energy and resource efficiency and minimising the energy and resource intensity of economic activities is usually the most cost-effective initial strategy to reduce carbon emissions and pollution; it also improves energy security. Energy and materials efficiency and a continued reduction in energy intensity has featured prominently in previous Chinese energy plans and should continue to be a major focus in the 2020s and beyond.

In IRENA's 1.5°C Scenario, energy efficiency and demand reduction account for around 25% of the global emission reductions needed to reach zero. In this scenario, the rate of improvements in energy intensity needs to increase to 3% per year (IRENA, 2021a), up from 1.2% in 2019 and previous years. China has made great progress in this regard over the last three decades, having reduced its energy intensity 70% between 1990 and 2018, an improvement that exceeds the global average (IEA, 2020a). Further reductions will be needed, however.

In China, there is still significant potential for efficiency improvements in many areas, such as industrial motor systems, buildings and urban service infrastructure (*e.g.* water supply and wastewater treatment, gas and electricity supply systems, and public lighting). In recent years, China has been increasingly receptive to the notion of the circular economy, which would improve the overall efficiency of resource management, reduce energy and material demands, and raise public awareness of conservation. Modern digital and communication technologies will unlock efficiency in operations, for example, making it possible to better optimise the transport of heavy goods and thus reduce overall energy consumption. There are also synergies to be exploited between the increasing electrification of end-use sectors, which can greatly improve the efficiency of energy service supply.

The potential for improvements in each sector needs to be analysed in more detail, particularly in the context of the continued industrial sector transformation.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Maintain a strategic focus on reducing energy intensity**
   China's energy strategy for the 2020s and beyond should continue to include a major focus on maximising energy and resource efficiency and minimising the energy and resource intensity of economic activities, particularly for energy-intensive industrial sectors.

2. **Exploit remaining opportunities for improvements**
   Areas of focus should include: accelerating the growth of the service sector and promoting a circular economy; identifying energy-saving potentials arising from new system and technological developments; implementing flexible mechanisms and business models with the priority of improving energy efficiency; and utilising digital technology to integrate various existing technologies to form comprehensive energy-saving solutions.

2.3 Accelerating the phase-down of coal consumption

China has a very strong track record in the adoption of renewable energy. However, a transition to net zero emission power systems will require new thinking and more fundamental reforms in both the technological and the market systems.

Reducing the use of coal

To achieve a peaking of emissions before 2030 and net zero by 2060, China needs to accelerate its phase-down of coal use for power generation, although coal would remain an important energy carrier into the 2030s. Ensuring that emissions peak before 2030 will require the development and effective implementation of detailed plans. Those plans will need to include some transitional measures that can deliver interim improvements in the clean use of coal, but such measures must not inhibit or be at the expense of the development of other clean energy technologies highlighted in this paper.

By 2050, in IRENA's 1.5°C Scenario, coal production globally will decline to around 240 million tonnes per year, from around 5 750 million tonnes today, a twenty four fold reduction. The remaining coal will be mostly used only in industry, primarily for iron and steel production (coupled with carbon capture and storage, CCS, and accounting for 5% of total steel production), with some role also in chemicals production. China's transition will need to follow a similar steep decline in coal use, with the remaining use concentrated in industry (IRENA, 2021a).

Beyond the direct impact on CO_2 emissions, reduction in coal demand can have wider impacts. The health implications of coal mining and particulate emission from burning coal are well documented. While China has taken major steps to reduce emissions from coal plants, such as its 2015 requirement for all coal plants to comply with "ultra-low-emission standards" before 2020, challenges remain (Wu *et al.*, 2019).

Reducing coal demand will have a profound effect on freight transport requirements. In China, more than half of all coal is transported by railway from coal mining regions or harbours to end users, including using rail lines built specifically to transport coal among regions. The rest of the coal is transported by either road or water.

The role of natural gas

The use of natural gas at scale has grown. China National Petroleum Corporation is one of the world's largest producers of natural gas, producing 150 billion cubic metres per year (CNPC, 2021). Some countries plan to use natural gas as a transition fuel to move away from coal and oil use, and globally natural gas will continue to contribute a large share of the energy supply even in 2050. However, this may not be a preferable strategy for China given its high dependency on imports. China imports 40% of its total gas supply, mostly as liquefied natural gas (LNG) but also some pipeline supply. Over time, China is expected to become the world's largest LNG importer.

China's existing natural gas infrastructure is still limited. This includes transmission pipeline capacity as well as storage capacity (geology limits the country's underground gas storage capacity) (IRENA, 2021a). Gas infrastructure in China is mostly dominated by three state-owned companies (Petro China, Sinopec and CNPC). Reform is under way to attract investment; however, given the eventual need to reduce use, such investments and reforms risk creating stranded assets and increased foreign dependency.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Curb emissions through the national emissions trading scheme, while reducing and eventually halting subsidies for coal production and use**
   - Progressively strengthen China's national emissions trading scheme to ramp up carbon emission reduction from the most emitting plants, notably coal-fired power plants. China should aim to reduce coal consumption during the period of the 15th Five-Year Energy Plan, which would be an important signal for the long-term transition away from coal.
   - While China has taken steps in recent years to reduce fossil fuel subsidies, it remains the largest provider of subsidies for coal exploration, production, processing, and transport, averaging around USD 4 billion annually during 2017-2019; it is also the largest provider of support to fossil fuel-based power, averaging around USD 38 billion annually during the period (IISD, 2020). As a share of GDP, China's fossil fuel subsidies put it in the middle of the Group of Twenty (G20) countries. All major economies need to remove these distortions, China included.

2. **Develop economic transition strategies for coal-reliant regions**
   Jobs and income from the increased production and use of clean energy technologies can fully replace the jobs lost from reduced coal use. Doing so requires careful planning, but there is a growing body of evidence and experience internationally on how to do so fairly. Through knowledge and experience exchange, China could make well-informed decisions on how to develop economic transition strategies for coal-reliant regions with as few adverse impacts as possible on local economies.

2.4 Accelerating the transition towards renewable power

At the same time as coal consumption is being scaled down, China's total power generation capacity needs to increase, using technologies consistent with the net zero goal. The 1.5°C Scenario envisages a tripling in electricity supply globally by 2050 compared to today's level, as the role of electrification and use of electrofuels (e-fuels) rises. In China, a similar trend is expected with power demand increasing significantly although slightly less than the global average, since China's electricity supply growth in recent decades has already been pronounced.

China's development of renewable power

Since China's implementation of its Renewable Energy Law in 2006, the rapid development of renewables has played an important role in reducing both atmospheric pollution and greenhouse gas emissions. In 2021, China's total installed renewable power generation capacity reached 1063 GW, accounting for more than one-third of the global total renewable power generation capacity and 44.8% of the Chinese total power generation capacity (Government of China, 2021). This momentum is set to continue. China aims to increase the share of non-fossil fuels in its primary energy consumption to 25% by 2030 – an increase of nearly 10 percentage points in a decade (from 2020). The combined installed power generation capacity of solar PV and wind turbines is targeted to exceed 1200 GW by 2030.

The cost of renewable power in China has dropped sharply over the past decade. IRENA's cost data show that the weighted-average total installed cost for onshore wind projects in China dropped 16% from USD 1500 per kW in 2010 to USD 1264 per kW in 2020, while the weighted-average levelised cost of electricity from onshore wind farms fell 47% from USD 0.071 per kWh to USD 0.037 per kWh. Solar PV has experienced more pronounced declines, with the weighted-average total installed cost for utility-scale solar PV projects in China falling 84% to USD 0.04 per kWh during the same period (IRENA, 2021b).

Renewables as the primary future source of energy

Renewables should be the preferred route for power generation, and in China renewable power should become the backbone of the power supply, making solar power, wind power and hydropower the dominant generation sources.

Renewables have the potential to supply 90% of total electricity globally by 2050, up from 25% in 2018. In IRENA's 1.5°C Scenario, renewable power installed generation capacity will need to increase from the current level of 2500 GW to close to 27800 GW in 2050. This requires a drastic acceleration to reach around 850 GW of annual additions in renewable electricity generation capacity – a four-fold increase from the current level (IRENA, 2021a).

Wind and solar PV will make the largest contributions, together supplying 63% of total global electricity needs by 2050, with solar PV installed capacity reaching more than 14000 GW and wind more than 8100 GW by 2050. Other mature renewable technologies (*e.g.* hydropower, bioenergy) with other technologies (*e.g.* concentrating solar power, marine and geothermal) will also play important roles. The role of solar and wind in China's power system has been on the rise and in many cases has been world-leading in recent years. This trend will only accelerate in the future, with the majority of electricity capacity and generation in China coming from these two key sources by 2050.

The potential of renewables as the dominant global energy source is driven by the dramatic cost reductions of recent years. The cost reduction is such that 75% of the onshore wind and 40% of the utility-scale solar PV commissioned in 2019 produced electricity more cheaply than any fossil fuel-based alternative, while more than 75% of the utility-scale solar PV and onshore wind commissioned in 2020 from auctions or tenders had lower prices than the cheapest new fossil fuel-based option (IRENA, 2020c).

These cost reductions mean that the adoption of renewables will not result in higher energy costs in China. By 2030, the levelised cost of electricity should be below 2 US cents per kWh across China, and not just in the western provinces. The share of renewables in primary energy supply globally will also see a large increase, from around 14% to 73%. Renewables will then become the primary source of energy in a climate-compatible world. To meet China's carbon neutrality aim, a similar trend will need to be followed.

While mature renewable technologies require accelerated scale-up, there is also significant potential in China for some emerging renewable technologies. Offshore wind (with either bottom-fixed or floating foundations) could play a significant role in the country, with offshore wind farms located close to coastal urban areas reducing the need for transmission from remote regions. China has become the global leader in offshore wind, with nearly 17 GW of capacity installed in 2021, according to the Chinese National Energy Administration (NEA, 2022).

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Exploit China's strengths and experience with renewables to accelerate deployment**
   China is leading the world in renewable energy deployment and now has the capacity and experience to lead the world in stepping up the deployment rate. Maximising solar, wind and hydropower should be the primary strategy for new capacity additions. The initial goal should be to sustain the annual deployment rate achieved in 2020, and to achieve a significantly higher rate by 2030. Renewables have the potential to supply more than 90% of China's electricity needs by 2050, with more than 60% of this coming from solar and wind. However, the transition would also require a systemic approach, particularly energy storage capacity and intelligent energy management systems to provide the flexibility that the future energy systems would need to maintain safe and reliable operations.

2. **Stimulate the development and uptake of emerging renewable technologies**
   In addition to actions to scale up mature renewable power technologies, China should continue to foster emerging technologies – in particular offshore renewables. Offshore wind (with either bottom-fixed or floating foundations) could play a significant role, with offshore wind farms located close to coastal urban areas reducing the need for transmission from remote regions.

2.5 Reforming power networks

Although renewable energy sources such as wind and solar PV are rapidly developing into the leading power sources of the future, their variability can bring challenges to the safe and stable operation of the power system. To counter this, power systems will need to become much more flexible to allow for the integration of high shares of variable renewable electricity.

In the 1.5°C Scenario by 2030, the variable renewable energy share in total power generation should reach 42% globally, and by 2050, 90% of the installed capacity and more than 63% of all power generation should come from variable resources (up from an average of around 20% of the installed capacity and nearly 10% of power generation globally today) (IRENA, 2021a). Shares of variable renewable electricity in China should be similar or potentially slightly higher, given China's renewable resource potential.

Decentralised, digitalised and electrified

Achieving this will require an energy system that should be increasingly decentralised, digitalised and electrified. China needs to consider how to change and re-optimise its power system from the traditional centralised system that currently dominates into a hybrid configuration that combines both centralised and distributed power generation systems. China also needs a more flexible inter-regional energy and electricity market to sustain the transition.

Marked regional differences exist in China: 70% of current hydropower generation is in the southwest, 80% of wind power generation is in the north, 60% of solar generation is in the west, and most power consumption is in the east and central regions (70%). Enhanced inter-regional trade will help make the most of these complementarities and balance supply and demand. This can then be supplemented with generation from local renewable energy resources and high use of storage technologies.

The deployment of more renewable energy in the networks of the State Grid and the China Southern Power Grid will require re-optimising the regional/national power grid system, including at the distribution network level to enable greater application of renewable-based distributed generation systems. Overall, well-designed power markets that encourage flexibility and maintain reliability at a low cost must underpin this future. Power markets should implement scarcity pricing to signal the need for flexibility, establish integrated multi-provincial spot markets, create a level playing field in spot markets for all resources, expose all thermal generators to spot market price signals and focus on spot market regulation.

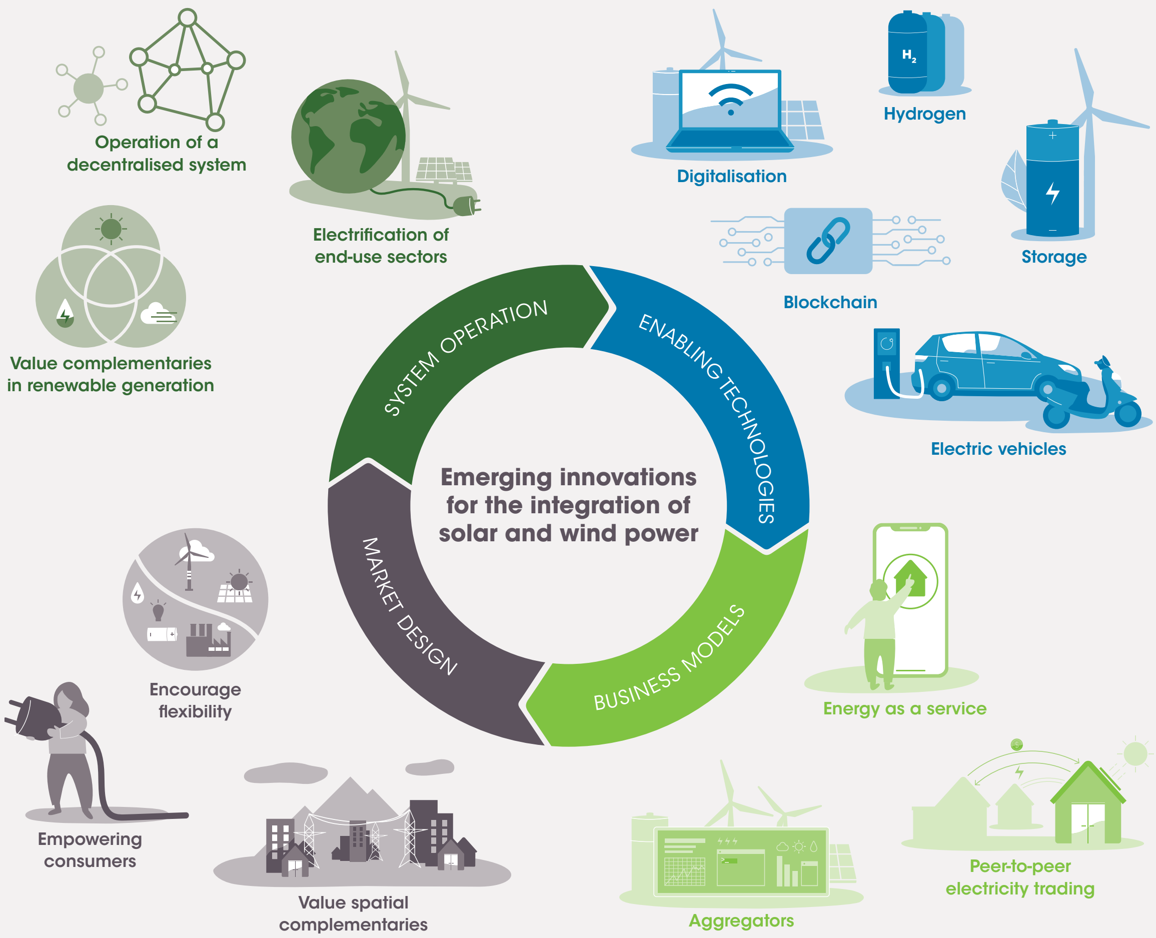
This will also involve the fuller use of digital technologies and a reform of the power market system, which will especially need further flexible market-based policies for those private companies with advantages in distributed/decentralised technologies and provision of grid services. There is also a need to link clean energy supply with the end-use sectors. Demand-side management and developing a competitive market with new players as aggregators are important. For example, electric vehicle charging companies need to be aggregated to give these vehicles a mass demand response capability to support high shares of variable renewable electricity. Smart charging could defer peak loads and reduce costs.

The characteristic of changing energy demand profiles – such as electric vehicles, distributed energy storage, demand response, etc. – is a factor of growing importance in the design of power systems. The management of this new load could either complicate or alleviate system operation (the latter by providing a source of increased flexibility to aid in the integration of variable renewable electricity).

Emerging innovations for the integration of variable renewable electricity

These changes can be enabled by the adoption of systemic innovations – an approach to facilitate the diffusion of innovative technologies with improved enabling environments such as business models, market structures, new regulations and overall system operations (Figure 1). Thus, the flexibility in the energy system could be improved, while more variable renewable electricity can be integrated in the power mix. IRENA's report *Innovation Landscape for a Renewable-Powered Future* (IRENA, 2019a), and its accompanying briefs, identified 30 flexibility options that can be combined into comprehensive solutions, taking into account national and regional power system specifics.

Figure 1 **Emerging innovations for the integration of variable renewable electricity – enabling technologies, market design, business models, system operation**



Adapted from IRENA, 2019a.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Continue to promote power market reform**
    - China needs a more flexible energy and electricity market to sustain the transition. Efforts under way to promote power market reform should be continued.
    - The inter-regional power market requires particular attention. There are marked regional differences in China, and enhanced inter-regional trade will help make the most of these complementarities and balance supply and demand. This needs to be balanced with energy generation from local renewable energy resources and high use of storage technologies.

2. **Accelerate the upgrade of electricity infrastructure**
    - Address the requirements of new electricity system optimisation and advanced electricity and its supported technologies and equipment, including smart grids, energy storage, distributed systems and other digital technologies.
    - Establish and implement a support mechanism to incentivise the demand for energy storage. Such mechanisms need to ensure that the cost of energy storage investment is reasonably shared by those stakeholders who benefit. In this regard, power market reform would need to take this into account and establish a proper market for the grid services that energy storage could provide.
    - Stimulate investment in ultra-high-voltage direct current transmission between the regional power markets.

Box 1 CDR measures and CCUS for power and industrial processes

In IRENA's 1.5°C Scenario, some emissions will remain by 2050 from the remaining fossil fuel use and from some industrial processes. There is a role therefore both for carbon capture and storage (CCS) technologies that reduce emissions released to the atmosphere and for carbon dioxide removal (CDR) measures and technologies, which, combined with long-term storage, can remove CO_2 from the atmosphere or oceans, resulting in negative emissions.

CDR measures and technologies include natural approaches such as afforestation and reforestation and technological/engineered approaches such as bioenergy with CCS (BECCS). Direct air carbon capture and storage (DACCS) and some other approaches are currently experimental. While the global potential for BECCS is 10.1 gigatonnes (Gt) of CO_2 per year by 2050, the 1.5°C Scenario assumes that BECCS will capture 44% of this, amounting to 4.5 Gt of CO_2 per year (up from current negligible amounts of less than 0.002 Gt per year). The most significant opportunities for BECCS are in power and co-generation plants and in the chemicals, cement, and iron and steel sectors. An additional 0.6 Gt of CO_2 per year is captured through carbon stocks in chemical products, recycling and carbon capture in waste incineration (IRENA, 2021a).

Box 1 (Continued)

DACCS technologies will play a role but are currently in the infancy stages of development. DACCS would likely take many years to reach the scale that would make a meaningful difference. Based on lessons from existing practices, projects would require high demand for energy, water and land, despite their locational flexibility. Further development and validation are needed before this potential can be properly evaluated.

The role of carbon capture, utilisation and storage (CCUS) in China's energy transition is more controversial, and although it is not the focus of this report its uptake has important implications for other technologies and hence requires some discussion here. Opinions in the global and Chinese analytical communities are divided as to whether CCS will play a major role in China's long-term carbon neutrality strategies, with some Chinese experts seeing only a limited role for CCS in decarbonisation and others arguing that it will play a major role.

In IRENA's analysis, CCS – *i.e.* the capture of CO_2 from point sources for its long-term storage – will have a role to play in a net zero strategy, but (with the exception of BECCS, discussed below) its use should be targeted and mainly limited to applications and circumstances where renewable options are not suitable or are initially more costly. In IRENA's 1.5°C Scenario (IRENA, 2021a), the role of CCS is limited to capturing process emissions in cement, iron and steel, blue hydrogen and chemical production, as well as limited deployment for industry/waste incinerators, etc.

Carbon capture and utilisation (CCU) applies to fossil fuel or process emissions and may have a limited role in the short term, improving the economics of early projects. It may also compensate for a lack of readily available and accessible CO_2 storage sites, but it should not have a significant role in the medium term since in many circumstances it can still lead to net emissions to the atmosphere. The use of CCU and CCS for process emissions would increase to 3.4 Gt of CO_2 captured annually in industry by 2050, up from 0.04 Gt today (IRENA, 2021a).

The number of CCS operational commercial plants globally is currently very small, but China is at the forefront of that exploration with several commercial plants in the power, coal-chemical and cement sectors. China has also carried out several pilot and demonstration projects in the iron and steel and coal-chemical sectors that are at various stages of development. Four projects, for example, are integrated full-chain CCS projects for enhanced oil recovery and storage of CO_2 in deep saline aquifers.

Transport and storage are two key factors when considering the siting of plants for cost-effective CCS deployment. There is, in principal, significant CO_2 storage capacity in China's main sedimentary basins. The location of storage sites, however, relative to the power and industrial processes and population centres, along with public acceptance concerns, may create challenges.

China should continue its leading role in piloting and developing CCS capability but with a focus on the targeted use of CCS and BECCS in those few areas where renewable solutions will not be sufficient.

2.6 Increasing the electrification of end-use sectors

China's goal of carbon peaking and neutrality requires fundamental changes in how the country both produces and consumes energy, and this will be no more evident than in final demand. There is a pressing need to determine how to best link rapidly expanding clean energy supplies with demand, and it is increasingly clear that the electrification of end-use sectors should be the first choice to make this possible.

Electrification as a primary route for decarbonising end-use sectors

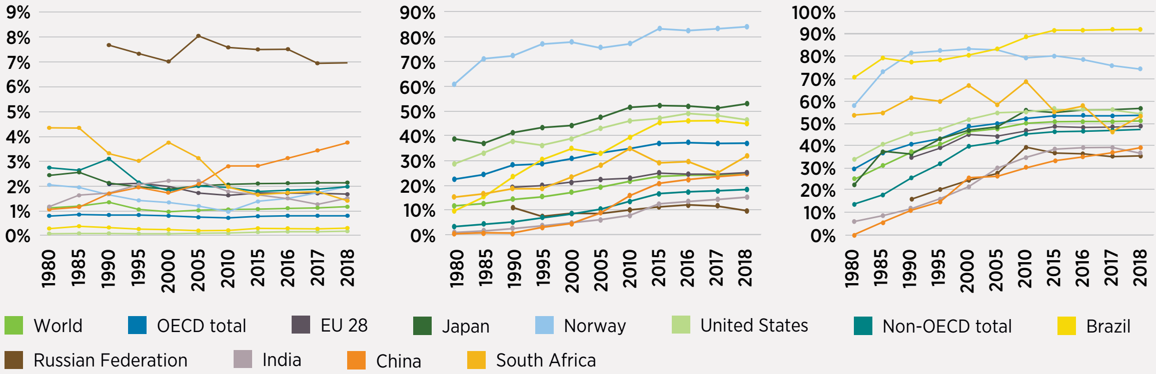
Dramatic reductions in the cost of renewable electricity (notably wind and solar PV) open up new cost-effective options for transport, industry and buildings. For a high proportion of end-use energy demand (greater than 50%), direct electrification will be the most efficient solution. The remainder will need to be addressed through the use of clean fuels and some limited legacy fossil fuel use (mostly natural gas).

IRENA is working with the State Grid Corporation of China to assess the potential of electrification with renewables. The work shows that electrification will have an increasingly important role in the world's energy transition, given the rapid technology development and the reduction in generation costs of renewable electricity. The technologies for a variety of end-use sectors to better use electricity – including electromobility, electric heating, hydrogen via electrolysis, and production of synthetic fuels – have been, albeit at various stages of development, progressing fast.

Electrification in China

In China, the combination of electrification and renewables is already starting to transform sectors such as light-duty road transport and buildings and is expected to contribute to substantial reduction of carbon emissions from the use of fossil fuel energy sources. In the last decades, electrification in those two sectors means that the overall rate of electrification in China is outpacing that of other major regions (Figure 2). Transport is an especially bright spot

Figure 2 **Electrification rate in final energy consumption (a), transport (b) and residential buildings (c) commercial and public buildings, 1980-2017**



Source: IRENA, 2022c.

in this regard: while Norway is the world champion in electric vehicle market growth, China has moved fast in accelerating adoption, representing around half of global passenger electric car sales and nearly 100% of global electric bus sales. China can continue to expand its world-leading experience in urban mobility electrification in cities like Shenzhen and Beijing – where entire bus fleets are shifting to electricity – to other rapidly growing urban areas.

While increasing the pace of electrification will be critical, a key message from the work of IRENA and State Grid is the need to avoid un-co-ordinated electrification, which could threaten to increase system peaks and cause issues for transmission and distribution networks. Smart electrification enabled by good planning and digitalisation will be a necessity to reduce peak loads, thus minimising the need for investments in enhancing grid options or adding more generation capacity. Increasing the flexibility of the loads to better match the outputs of variable renewables would help to increase the use of variable renewable electricity in the power mix and allow other sectors to use renewable electricity. This can be achieved through, for example, load shifting, smart technologies, and the production and storage of green hydrogen.

China already has experience with such smart electrification strategies to take full advantage of low-cost variable renewable electricity. The country could build on power-to-heat efforts such as those in the Inner Mongolia Autonomous Region, for example, where the installation of electric boilers in district heating systems would make use of the region's major wind power capacity that otherwise would be curtailed due to transmission constraints.

Low-cost capacity of variable renewable electricity also pairs extremely well with new and innovative demand-side management initiatives like smart charging of electric vehicles, or aggregators that give electric vehicles a mass demand response capability. The push to build extensive smart electric vehicle charging networks in China – which had more than 450 000 charging stations by the end of 2017 (GSEP, n.d.), as well as State Grid's Smart EV-to-Grid Service Network (SEGSN) – can be continued to ensure that transport electrification does not overwhelm the grid.

Opportunities for deeper electrification

While China is already making significant progress in areas such as the electrification of transport and buildings with electric vehicles, district heating systems, electric boilers, and heat pumps, even more opportunities for low-cost electrification with renewables will present themselves in the coming years:

- In buildings, heating and cooling can be provided by heat pumps, which deliver greater efficiencies. More importantly, when heat pumps can be controlled by smart electricity meters/thermostats, they essentially serve as a flexible load responding to demand management schemes, if any.

- For the built environment, especially in areas with high population density, district heating and cooling options with heat pump technologies in China would make better technical and economic sense compared to individual heat pumps. The network can also offer an opportunity for more diversified sources of heating and cooling, including energy storage, than a system with only electricity as a source to meet such thermal demand.

- Large seasonal differences in regional climate will be important to consider in China's electrification process. An increasingly promising solution appears to be seasonal thermal energy storage, if the scale that China would need can be developed in a cost-competitive manner.

- For industry, especially for energy-intensive sectors, the relocation of operations to regions with abundant renewable energy sources would allow industries to benefit from cost-competitive renewable electricity while reducing their carbon footprints. A promising practice along these lines is using green hydrogen to substitute coke coal as a reduction agent in the iron-making process. This could be applicable for China, as the country's major iron ore reserves are located in the west where excellent renewable energy resources are present.

Innovation is already enabling such strategies, and IRENA's upcoming *Innovation Landscape for the Electrification of End-Use Sectors* report will provide a comprehensive assessment of the emerging systemic innovations that can unlock further potential of electricity in transport, buildings and industry.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Develop a long-term vision of the role of electricity in the country's energy system**
   Ensure that the specific vision for electrification is reflected in long-term roadmaps and plans for building or expanding smart electrification infrastructure, including transmission and distribution grids, charging networks, facilities and pipelines for hydrogen production and distribution, and district heating and cooling systems.

2. **Accelerate implementation**
   - Continue to scale up smart charging infrastructure and support digital grid technologies and solutions such as SEGSN to manage new patterns of load, to optimise the use of variable renewable electricity, and to explore technologies that offer synergies among sectors.
   - Expand on efforts in China that take advantage of large-scale centralised solutions such as district heating and cooling, and fleet electrification for urban mobility.
   - Explore the relocation of energy-intensive industries to sites with low-cost renewable power, such as the western and northern regions of China, provided that the other critical factors for production can also be satisfied.

3. **Adapt regulations**
   - Further promote price reforms (including for electricity, natural gas, heating and water), and use price signals.
   - Remove barriers to innovative technologies or ownership models.
   - Provide incentives or funds for the widespread adoption and use of heat pumps, electric boilers, and smart meters and appliances.
   - Strengthen building codes to require greater efficiency in buildings, and support weatherisation of existing buildings.

2.7 Expanding the direct use of renewables, particularly biomass for energy purposes

Solar thermal, bioenergy and geothermal will be further needed at greater scale to provide zero-carbon thermal energy for space heating and cooling (absorption chillers) and hot water in buildings, as well as for industrial processes, through direct use of the resources. In the 1.5°C Scenario the direct use of renewables (*i.e.* solar thermal, geothermal and bioenergy) would need to grow to almost 22% of total final energy use by 2050, providing 78 exajoules (EJ) in 2050 compared to 44 EJ in 2018 (IRENA, 2021a).

Bioenergy as an essential pillar in delivering carbon neutrality

Bioenergy (including the traditional use of biomass) constitutes the bulk of today's global renewable energy use and accounts for around one-tenth of the global total final energy use. Bioenergy has key roles as a source of energy and as a feedstock that can replace fossil fuels in some industrial end-use sectors, and it can contribute to balancing an electricity grid that has high shares of variable renewables such as solar PV and wind. Bioenergy technologies are developing rapidly and have significant potential to scale up by 2050.

In the 1.5°C Scenario, the share of final energy demand that can be met with modern forms of bioenergy increases to 17% in 2050, from 1.5% today. Meanwhile, traditional uses of bioenergy, which account for a large share of today's biomass use, must be replaced with modern bioenergy technologies (IRENA, 2021a). In China, modern biomass, as well as waste-to-energy feedstocks, are underutilised resources that will require new strategies to ensure that they are exploited sustainably.

In those sectors known as hard-to-abate, including energy-intensive industrial sectors such as iron and steel, cement, aluminium, and chemicals, as well as certain segments of the transport industry, bioenergy can have an important role to play:

- In the transport sector, despite the recent uptake of electric vehicles, which are more suitable for light-duty and short-distance transport, biofuels can provide better performance to meet long-haul or heavy-freight transport needs. IRENA's study shows that in a scenario that aims to keep global temperature rise to below 2°C, we will need 652 billion litres of liquid biofuels by 2050, representing a five-fold increase from the 2017 level (IRENA, 2020b); this also suggests that a net zero goal will require even higher volumes.

- In the buildings sector, biomass has been used to provide heating supply through district heating networks that in some cases are connected to biomass-based combined heat and power (CHP) plants or individual furnaces. Such applications can be scaled up in the future.

- For some industry sectors such as chemicals, biomass offers a viable option as a substitute for fossil-based feedstocks for production and for fossil fuels in providing low- to medium-temperature heat. In addition (as discussed in Box 1) biomass with CCS will be needed globally for some power production and industrial processes, for instance in cement production.

However, in addition to competing uses of biomass for different applications, the costs of producing biofuels and biomass-based feedstocks for industrial sectors would have to be further reduced. The sustainability of feedstock supply will continue to be a critical factor for enabling greater application of biomass in these end-use sectors. Therefore, wherever needed, a proper risk assessment for bioenergy use, including environmental and social impacts, should be performed. IRENA's analysis suggests that the levels of biomass needed to deliver the 1.5°C scenario can be met without adverse impacts on forestry and other land-use purposes, if effective measures in regulation, certification and monitoring are taken.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **More fully integrate the use of biomass in both energy system and rural development plans**
   Biomass has been broadly used in many sectors such as food, feed, fertiliser and energy. Its energy applications account for only a small portion of the emerging bio-economy but could potentially scale up dramatically. The synergies of bioenergy applications with other sectors such as agriculture and forestry can be created. Therefore, China should establish cross-sectoral co-ordination mechanisms among energy, agriculture and forestry policy makers to ensure a fully integrated approach in planning the use of biomass as a feedstock for energy and other purposes.

2. **Address challenges in rural biomass energy use**
   At present, nearly 1 billion tonnes of agricultural and forestry residues in China could be used for energy purposes, and 1.8 billion tonnes of livestock and poultry manure is available annually for conversion into biogas and organic fertiliser (NFA, 2021). Alongside solar PV and wind energy, these resources could form an "energy agriculture" industry. Rural areas can be both energy consumers and energy suppliers. China should prioritise the sustainable use of various organic wastes (agricultural and forestry residues, domestic waste, livestock and poultry manure, fruit and vegetable waste, domestic sewage, etc.) in rural areas, and comprehensively consider rural energy and waste strategies that promote new forms of production and rural employment.

3. **Promoting biorefineries to create greater value among various biomass-based end users**
   Biorefineries can use biomass in a more sustainable and efficient way, and their products can meet the needs of different applications, thus creating greater value for biomass as a feedstock as well as for end users. Biorefineries will also help better reconcile the use of biomass for bioenergy purposes and to produce bio-based industrial materials. China therefore should establish a platform for multi-stakeholder communication and exchange of knowledge in promoting the adoption of biorefineries as a key component of building the integrated infrastructure for future biomass applications.

4. **Integrate novel technologies for CCUS with bioenergy**
   BECCU/S might offer the potential to reduce carbon emissions in some industrial sectors; if well managed, the technology can also absorb carbon that is already in the atmosphere, thus realising negative emissions. Although more pilot projects have been established over time, there is still a lack of large-scale application, indicating the uncertainty of technology cost outlooks. China could better evaluate the potential of BECCU/S and develop a strategy that would nurture its technological development and support its deployment through demonstration projects at the initial stage.

2.8 Scaling up the production and use of hydrogen and synthetic fuels

Hydrogen can offer a solution for types of energy demand that are hard to directly electrify. Alongside the direct use of renewables discussed above, it can address some of the roughly 50% of final energy use that may not be suitable for direct electrification due to technological, logistical or economic factors (IRENA, 2020d).

Current global hydrogen production is around 120 million tonnes (Mt) (14 EJ) annually, of which 33 Mt is produced in China, and it is almost entirely fossil-based. Looking forward, hydrogen and its derivatives will be able to provide 12% of global final energy use by 2050, as shown in IRENA's 1.5°C Scenario. An estimated two-thirds of this would be produced using renewable electricity, *i.e.* green hydrogen. Producing this will require dedicating 27% of the generation capacity in 2050 to green hydrogen production, or 21 000 TWh of electricity demand by 2050 (IRENA, 2021a). China's use of hydrogen can grow up to four times by 2050, with the bulk of the growth driven by the industrial sector.

Delivering this will require a significant scale-up in electrolyser manufacturing and deployment. Globally around 5 000 GW of hydrogen electrolyser capacity will be needed by mid-century, up from just 0.3 GW today, which will require around 160 GW of electrolysers to be installed annually on average during the period to 2050 (IRENA, 2021a). Currently less than 1% of global hydrogen production is green hydrogen. Yet, along with continued reduction in the cost of green hydrogen production, China is expected to play a key role in the hydrogen industry, not only as a source of demand and as a supplier of electrolysers but also as a producer of green hydrogen, given the rapid growth in renewable electricity generation capacity (IRENA, 2020e).

China will play at least two key roles in the hydrogen industry. First, the size of energy demand and the economy can represent a driver for hydrogen. China had 540 GW of renewable capacity in 2020, and accounts for 60% of global steel production, and for 30% of ammonia, methanol and high-value chemical production. A small share of these industries could represent a large hydrogen demand and electrolyser deployment, given China's scale.

Second, China has the advantages of large industrial activity and relatively low labour costs, which can provide the conditions to become a supplier of electrolysers to other countries. China already has large electrolyser manufacturers (such as the research institute of China State Shipbuilding Corporation (PERIC), Cockerill-Jingli Hydrogen and TianJin Mainland) as well as a lower capital cost for electrolysers produced. However, according to the *China Hydrogen Energy & Fuel Cell Industry Development Report 2021* from China's Hydrogen Energy & Fuel Cells Industry Innovation Strategic Alliance, Chinese electrolysers have lower efficiencies and shorter lifespans compared to their western peers due to the technologies and materials used (Heyward, 2022). This implies that China would need a greater level of technological innovation to improve the performance of its electrolysers

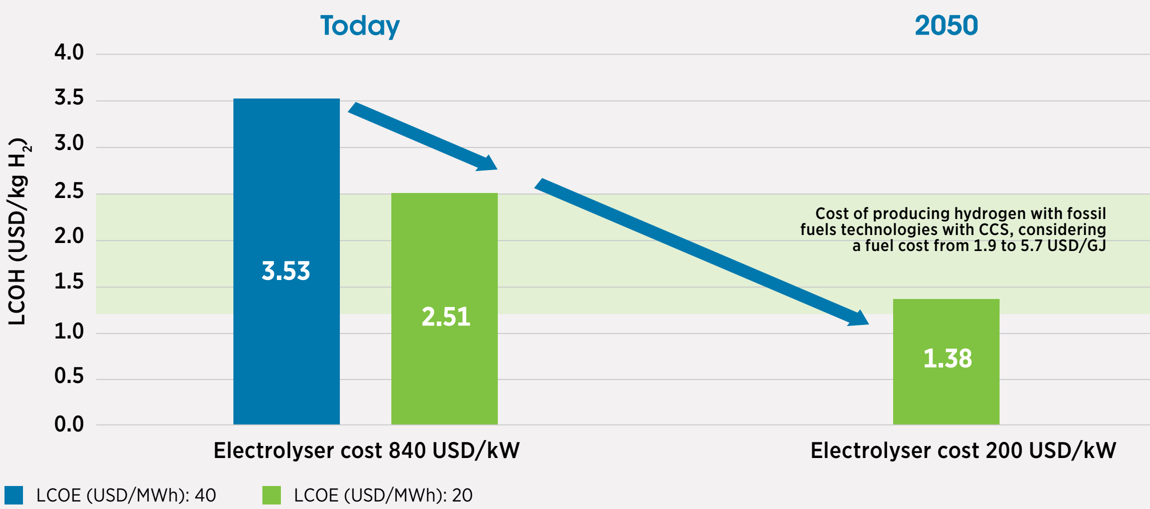
Green hydrogen's potential

There is substantial potential to scale up green hydrogen production in China, although it will be important to ensure that any renewable capacity used for hydrogen is additional to the planned activities and that hydrogen is not displacing more efficient uses of electricity (*i.e.* direct use). This is especially relevant for China, since the power sector has a 28%

renewable share but coal represents nearly two-thirds of the generation (Gielen, Chen and Durrant, 2021). If such additionality in deploying renewable power generation capacity is not ensured, renewables could end up being used substantially for hydrogen production, thus delaying the phase-out of coal plants in providing electricity for consumers.

China has excellent wind resources in the northern provinces that can reach capacity factors of above 50%, as well as excellent solar resources in the Tibet-Qinghai plateau in the western provinces. This can potentially lead to electricity prices of around USD 30 per megawatt hour (MWh) in the near term at these locations and a more widespread cost of USD 20 per MWh by 2030. These low costs would allow green hydrogen to become the most competitive pathway for hydrogen production. Green hydrogen can already be produced at costs competitive with blue hydrogen today, using low-cost renewable electricity, *i.e.* around USD 20 per MWh. If rapid scale-up takes place in the next decade, green hydrogen is expected to start becoming competitive with blue hydrogen by 2030 in a wide range of countries (Figure 3).

Figure 3 **Hydrogen production costs, 2020-2050**



Note: Assumes a load factor of 4 200 hours and conversion efficiencies of 65% in 2020 and 75% in 2050.
Source: IRENA, 2019b.

Green hydrogen applications

Hydrogen can be ten times cheaper to transport than electricity, so green hydrogen could also provide a way to connect the renewable resources in China's northern and western provinces with the industrial and urban areas located in the country's east and south-east. In addition, green hydrogen can contribute to integrating more renewables in the power sector by providing additional flexibility and can provide seasonal storage complementing short-term storage (*e.g.* batteries).

Areas to consider for green hydrogen use in China in the near term include:

- **Industrial use:** Industry represents around 60% of final energy demand, while at the same time industry is the dominant hydrogen use today, reaching almost 25 Mt per year of hydrogen. Almost all this hydrogen is produced today from coal gasification. Starting to satisfy part of this demand with green hydrogen would allow for scaling up electrolysers and contribute to cost reduction. Furthermore, the chemical sector is still growing, which means that green ammonia and methanol do not need to displace existing production but can instead satisfy new demand (IRENA and AEA, 2022). For this, industry would require incentives to promote fuel shifting (*e.g.* expansion of the emission trading system coupled with a reduction in free allowances) in tandem with border carbon adjustments or mechanisms to ensure maintenance of global competitiveness.

- **Innovation:** Many of the critical hydrogen use pathways still require demonstration and experience. Direct reduction for steel making, ammonia for ships and synthetic fuels for aviation are still in the early stages of development, while also representing critical pathways for a net zero emission system. The main challenge for these three sectors remains the need for international co-ordination and global competitiveness. However, early efforts on technology demonstration in the short term might have limited impacts in the overall sectors.

- **Electrolysis:** China already has multiple electrolyser manufacturers that have built up experience and could satisfy the domestic market with domestic technology. There are some indications that already today the electrolyser cost in China is lower than in some projects in Europe. Taking advantage of low labour costs and supply chains that have been scaled up for industrial manufacturing, China could attain leadership in electrolyser manufacturing. Knowledge developed for this step could also lead to technology spillover and be useful for fuel cells, which open up a broader range of possibilities for end uses, from stationary power generation (across all scales) to mobile applications (*e.g.* transport). This would also be in line with the industrial plan for China (Made in China 2025), which aims to acquire technology leadership in green energy.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Develop a supportive policy framework**
   Introduce policies that encourage fuel shifts in industry and expand the scope of eligible fuels to hydrogen and its derivatives. In parallel, explore regulatory measures to address the risk of carbon leakage to enable hydrogen use while maintaining industrial competitiveness.

2. **Demonstrate and build experience in hydrogen end-use applications**
   These include the direction reduction of steel, ammonia for ships and synthetic fuels for aviation. These pathways are at early stages of deployment but will be critical for achieving a net zero energy system, and China could attain global leadership in these technologies.

3. **Support the domestic electrolyser industry**
   Already today multiple Chinese manufacturers are providing low-cost electrolysers. Government support could enable growth, learning and competition leading to technological leadership for China.

2.9 Supporting cities as champions of low-carbon living

China's urbanisation over the past half century has been remarkably rapid and practically unique in scale. City dwellers now make up 60% of China's population of 1.4 billion (State Council, 2020), and the country's 14th Five-Year Plan projected that the share of permanent urban residents would reach 65% by 2025. Yet the migration that helped bring millions out of poverty has sharply increased urban energy consumption. It has also degraded the environment in and around cities. The resulting challenges have brought China to a crossroads in energy and environmental security.

Cities, and their surrounding areas, represent around 85% of China's energy demand, and the country is contemplating how it can sustain continued urbanisation for another three decades, with a further 255 million city dwellers set to be added (UN, 2018). This calls for a long-term energy transformation at the city level.

Cities are diverse, making it extremely challenging to find a one-size-fits-all solution. Industry accounted for around 70% of the urban final energy consumption in China in 2016 (although this share has been declining since 2012), while buildings accounted for around 19% and transport for 11%, according to the State Grid City and Energy Research Institute (SGCERI, 2019). Global experiences suggest that cities are more likely to take action if they set concrete and attainable targets for energy transformation. To make this happen, there is a need to develop a long-term energy strategy/plan with clearly defined directions.

The future urban energy infrastructure will be shaped by today's investment decisions and urban planning. Sustainable solutions must be identified from a long-term, system-wide perspective to avoid the creation of stranded assets. An effective analysis framework to identify solutions for cities should include bottom-up planning elements that reconcile with the long-term low-carbon urban and regional energy strategies (IRENA, 2020f). For example, provincial and municipal-level planning should be co-ordinated effectively on how to decarbonise the energy mix, in ways consistent with national strategic objectives.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Encourage local authorities to develop long-term integrated urban planning**
   Such plans should have twin aims to achieve carbon neutrality and better liveability.

2. **Prioritise distributed energy generation**
   Urban energy supply should be based on maximised use of local renewable energy resources with the support of coupling end-use sectors and urban infrastructure, digitalised intelligent energy management systems and improved energy efficiency.

3. **Contribute to energy system flexibility**
   Cities can contribute to enhancing the overall flexibility of the energy system through making the urban energy demand more responsive to generation from variable renewable electricity from the national grid.

4. Reform urban waste use
China's huge municipal waste is a very large market for indirect carbon emission reduction. The collection and treatment of waste should be reformed to incentivise recycling and appropriate disposal, including through a charging system.

Box 2 City case study: Urban energy transformation in Zhangjiakou

IRENA and Zhangjiakou Municipal Government have been exploring urban energy transformation for Zhangjiakou city towards 2050. The Zhangjiakou case study shows that important practical barriers exist at the municipal level that need to be considered, such as co-ordinated long-term planning across the energy and industrial sectors, diversification of end uses for renewable energy applications, the role of hydrogen in the future economy, policy innovation, and institutional capacity enhancement (including being empowered through advanced urban energy planning).

As the first of its kind in China, the Zhangjiakou Energy Transformation Strategy 2050 has set a new paradigm for many other Chinese cities that are eager to wean their energy systems off coal and to take advantage of the uptake of renewable energy technologies and other enabling technologies such as electric vehicles, hydrogen production and applications, battery storage systems and smart grids. More insights related to cities can be found in the report *Zhangjiakou Energy Transformation Strategy 2050* (IRENA, 2019c) and forthcoming IRENA work in this area.

2.10 Continuing progress in light-duty transport and broadening to heavy-duty and long-haul modes

Falling costs and rising shares of renewable energy in China's electricity supply system open the door for transforming the transport sector, mostly centred around direct and indirect electrification. Rail transport is already largely powered with electricity, and while the preferable path to lowering CO_2 emissions is relatively clear for light-duty road transport, the optimal approach is less certain for heavy-duty road freight transport, shipping and aviation.

Reducing emissions from transport can be achieved through behavioural changes, urban planning and improved fuel efficiencies. Yet these instruments can hardly yield the results of a full decarbonisation of the sector. To transform the sector to carbon neutrality, the technological options that can accelerate such transformation include the direct use of clean, preferably renewable, electricity (for rail and road transport, including heavy-duty road freight transport); the use of green or blue e-fuels, such as hydrogen, ammonia and other e-fuels (particularly for shipping and some heavy-duty road freight transport); and the use of biofuels (particularly for aviation).

The wider use of electricity in transport would have been viewed as a luxury solution just a few years ago, due to the then-higher costs of both renewable electricity and batteries in addition to the manufacturing cost. However, in recent years the continued decrease in generation costs has made electricity from renewable energy sources cost competitive in many regions across the globe; this is coupled with scaled-up battery sizes and electric vehicle manufacturing capacities and improved technological maturity – two important factors leading to the cost decline.

Against this backdrop, electrification becomes a very promising scenario for decarbonising the transport sector. Hydrogen-based technologies will play an important role in this decarbonisation for all transport modes, but particularly in shipping and aviation where hydrogen and synthetic fuels are expected to account for around 60% and one-quarter, respectively, of yearly final energy consumption by 2050 in IRENA's 1.5°C Scenario (IRENA, 2021c).

Biofuels can also offer technologically mature options to use as viable substitutes for petroleum-based transport fuels because they require no or minimum retrofitting of vehicle engines when the blending ratios are within certain levels. In addition, biofuel production could bring co-benefits to rural development, spur the development of agro- and wood industries, and create extra revenue streams for municipal waste management, thus advancing the circular economy as some portion of the wastes can be used as feedstock for producing biofuels such as biodiesel and biogas.

There are still some barriers to be removed for such options to reach their full potentials contributing to the transport sector transformation. IRENA's *Reaching Zero with Renewables* report (IRENA, 2020a) explores the options in detail, supplemented by deep-dive reports including on shipping (IRENA, 2019d, 2021c) and on aviation biojet (IRENA, 2021d).

Road transport

Passenger and light-duty road freight transport

For passenger vehicles and light-duty freight road transport, battery electric vehicles have demonstrated great advantages in recent years in technology, cost competitiveness and market share. In many countries, electric vehicles account for a growing share of new light-duty vehicle sales, with the global leader being Norway where electric vehicles comprised 54% of all cars sold in 2020 (Reuters, 2021).

China is already a leader in electromobility, as shown in Figure 2; however, better understanding is still needed on several issues, including the extent to which the electric grid can support the substantial increase in electricity demand for vehicle charging; how to couple charging with variable renewable energy production; and the measures needed to manage the charging processes, including smarter charging infrastructure that can provide charging services for several cars synchronously. These aspects will be critical, as electric vehicles are expected to reach around 80-90% of road passenger activity in China 2050, an increase that will lead electricity consumption from road passenger vehicles to increase around twenty five fold.

Critical issues for an increased scale-up of electric vehicles are: improving battery performance, lowering battery costs, deploying smart and rapid charging technologies, understanding parking and charging behaviours, and ensuring adequate supply of critical materials needed for electric vehicle manufacturing. Additional insights on electric mobility can be found in the IRENA reports *Innovation Landscape for a Renewable-Powered Future* (IRENA, 2019a), *Innovation Outlook: Smart Charging for Electric Vehicles* (IRENA, 2019e) and *Critical Materials for Energy Transition: Lithium* (Gielen and Lyons, 2022).

Heavy-duty and long-haul freight road transport

As vehicles become heavier and travel longer distances, the challenges for their direct electrification increase. This is true not only for heavy-duty road transport, but also for aviation and long-distance shipping. The heavier a vehicle is, the more battery power it needs (*e.g.* a heavy-duty long-haul truck will need a battery that is 15 times larger on a kWh-basis than a Tesla Model X battery) (IRENA, 2020a). Despite this, direct electrification with batteries, assuming an improvement in battery performance, is one credible possible pathway for the decarbonisation of heavy-duty road freight transport. Direct electrification is the most efficient pathway, and by 2050 it is expected to play a prominent role in the decarbonisation of Chinese road freight transport.

The deployment of catenary lines along highways could ease this transition. However, if battery improvements do not reach the necessary level for their widespread deployment in commercial trucks, the use of hydrogen cells powered with clean hydrogen is also a zero-emission alternative. Finally, liquid biofuels may be used across all transport sectors, including road transport, which presently consumes 212 petajoules of liquid biofuels yearly and is by far their largest consumer and likely to remain so (although aviation and shipping hold greater potential in terms of market growth given that the other alternative options are largely in the infancy stage).

Even though transporting goods via rail or shipping is cleaner than road transport, the majority of Chinese commodities (including coal) are transported by road. Modal shifts from road to rail or water would be beneficial from an energy consumption and emission perspective. Rail transport uses around one-seventh the energy needed to move the same goods by road and produces one-thirteenth the pollution, while transport by water uses one-fourteenth the energy and produces one-fifteenth the pollution (Baiyu, 2020).

Aviation

Aviation is also a significant energy user and CO_2 emitter, and bringing its emissions to net zero by 2060 will be a challenge since this decarbonisation cannot fully rely on direct electrification. China is the second largest aviation market in the world, trailing behind only the United States; it is also the fastest growing market (pre-pandemic), with 7.8% growth in 2019 (IATA, 2020. China plays a key role in the global economy as a powerhouse of manufacturing, exporting goods all over the world. The aviation market in China is expected to grow 5.3% annually until 2038 – exceeding projected global average growth of 3.8% annually – and is expected to become the largest market as soon as 2022 (IATA, 2020). This means that China will be key to realising the carbon neutrality of global aviation.

Aviation has limited alternative fuel options for decarbonisation, due mainly to the physics of aircraft and flight. Therefore, decarbonising the sector, both globally and in China, will rely on a mix of solutions that include reducing demand through modal shifts and enhanced communications technologies, and replacing jet fuel with synthetic jet fuel or biojet. The use of synthetic fuels and biojet face similar barriers in costs and production volumes. Electrification is also expected to play an important, albeit secondary, role in aviation (accounting for around a fifth of energy consumption), mostly for small aircraft and short-distance flights.

Shipping

China is the world's largest exporter and ship builder and is in a unique position to lead the transition to zero-emission shipping. The momentum to decarbonise shipping is at an all-time high, with some of the largest shipping companies having made commitments to eliminate their carbon emissions by 2050. China, a member of the International Maritime Organization and a supporter of its efforts on sustainability, must be prepared to transition towards zero-emission shipping, or risk losing its position as a worldwide leader in shipping (Molloy, 2019).

In terms of technology, international shipping is expected to rely largely on synthetic fuels to replace conventional marine fuels. Green ammonia is a particularly interesting option and is being increasingly cited as the best option by many parties. Ammonia is easier and cheaper to handle than hydrogen and has no carbon emissions, unlike methanol, although it does release nitrous oxide emissions that need to be scrubbed. Direct electrification can also play an important role in shipping, especially in domestic and short-distance shipping.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **For domestic transport:**
   - Continue the roll-out of electric vehicles and charging infrastructure for passenger transport, and ensure that charging infrastructure is "smart".
   - Develop integrated roadmaps for transport sectors including for the role of hydrogen in transport and a decarbonisation plan for heavy vehicles.
   - Exploit possible shared impetus from other sectors, such as incentives for lowering the cost of batteries that would benefit more than just the transport sector; increased demand for cost-competitive green hydrogen and the established supply chain for green hydrogen use; and the supply of sustainable sources of feedstocks for biofuels.

2. **For international aviation and shipping:**
   - Building on the overall effort to reduce carbon emissions in China, develop a carbon neutrality strategy for the aviation sector.
   - Incentivise the adoption of low-carbon flight options by raising fuel standards, encouraging corporate commitments to low-carbon practices, and facilitating investment in innovative technologies and scale-up of the deployment of mature technologies.
   - Conduct more detailed studies on the realistic potentials of key alternative fuels such as biojet and synthetic fuels that are applicable for various use cases, to inform policy makers and industry players of the potential trade-offs and competing use of feedstocks and products within and beyond the aviation sector.

2.11 Laying the groundwork for industrial sectors to achieve net zero emissions

The industrial sectors have been a critical element in powering the global economy. Contributing around 28% of global carbon emissions, they are also a major emitter. The use of fossil fuels as the key energy source in industry is only part of this emission contribution. Emissions also come from industrial production processes and from the life cycle of products. This makes achieving the net zero goal for industrial sectors both challenging and important. The four most energy-intensive industry sub-sectors – iron and steel, chemicals and petrochemicals, cement and lime, and aluminium – emit around 75% of the total emissions from the entire industrial sector (IRENA, 2020a).

The challenge of energy-intensive industries

To reduce carbon emissions from energy-intensive industrial sectors is technically a daunting task, particularly for the four dominant sectors. Furthermore, much greater policy attention is needed to generate the necessary resources to address the challenge. This is attributable to two key factors: 1) lack of proven best practices for reducing emissions in a technically and economically viable manner; and 2) many industrial products are globally traded commodities, generating valid concerns about carbon leakage and industrial competitiveness if only some countries opt to pursue industrial emission reduction.

Energy efficiency improvements have been pursued in industrial sectors, but they have their limitations and cannot be used alone to achieve the net zero emission goal. Innovations beyond enhancing energy efficiency are needed to reduce the large quantities of emissions from the most energy-intensive industrial sectors.

All four of these sectors are stepping up their efforts to develop emission reduction strategies and are testing new technologies and alternative industrial production processes. But these efforts have a long way to go to reach net zero by mid-century. Given the limited resources and time left, a more strategic and clear focus is required to establish which decarbonisation pathway to take.

China dominates the production of some energy-intensive industrial products

The dominance of industrial manufacturing in China makes achieving net zero emissions in the sector uniquely challenging for the country, compared to other large economies. China's industrial sector accounts for 60% of gross final energy use (for both energy and non-energy uses), and two-thirds of industry energy demand is met by coal (with another quarter met by electricity). This results in around 4 Gt of energy-related CO_2 emissions and 2 Gt of process-related CO_2 emissions, together accounting for just under two-thirds of China's CO_2 emissions (Grant and Larsen, 2020; Liu *et al.*, 2019). Within the industrial sector, emissions from energy-intensive industries such as iron and steel, aluminium, chemicals and petrochemicals, and cement and lime account for the lion's share and are not expected to decline significantly during 2020-2050 without stronger policies in place, according to IRENA's analysis (Figure 4).

This makes action on industry critical to China's carbon neutrality goals. Given the country's role in the global industrial landscape, Chinese action to achieve net zero in industry is also critical for the success of the global industrial energy transformation. Moreover, what China does (and does not) do will have implications for industrial competitors around the world.

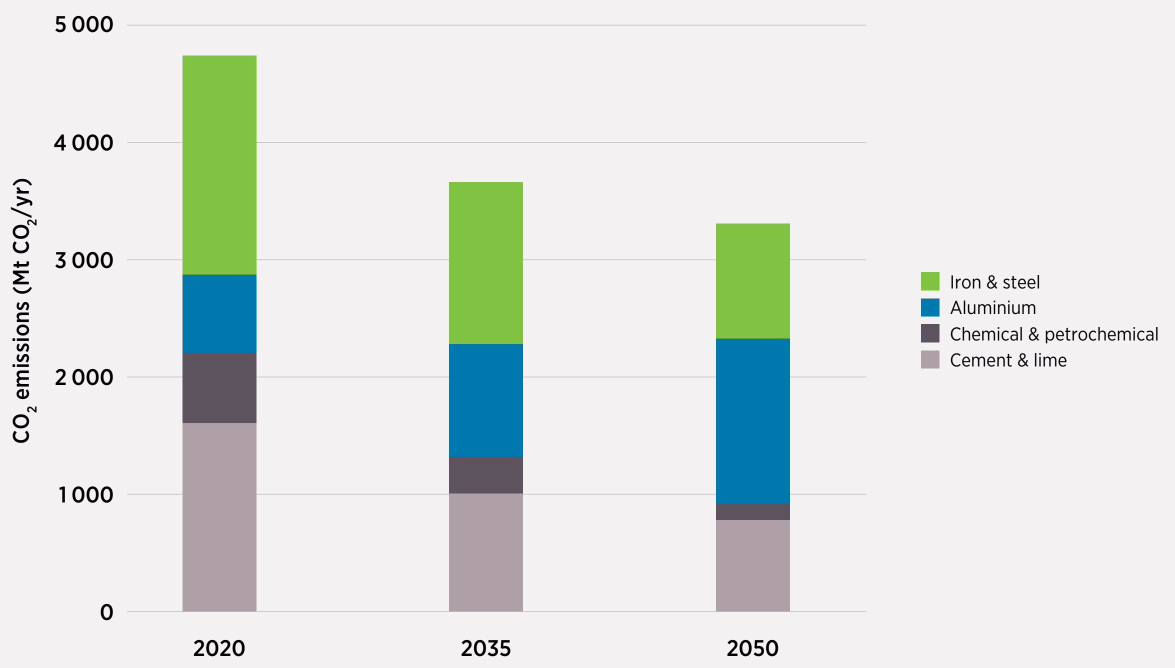
Actions in key energy-intensive industrial sectors include the following:

- **Cement:** In 2019, half of the world's cement was produced in China, which has 2.33 Gt of production capacity. More importantly, the Chinese clinker-to-cement ratio has reached 0.65, with 1.52 Gt of clinker output in 2019, within the lowest range in the world. Given that emissions from the cement sector arise chiefly from the clinker production process, this low ratio is of great significance (CemNet, 2020).

- **Iron and steel:** China represented more than half of the global output of crude steel in 2019, with 996 Mt of production (WSA, 2020). However, nearly 90% of Chinese steel was produced through the basic oxygen furnace (BOF) route, whereas steel produced using recycled steel scrap through the electric arc furnace (EAF) process accounted for only 10% or so. This is well below the world average.

- **Aluminium:** China produced 35.8 Mt of electrolytic aluminium in 2019 (IAI, 2021), representing 56% of the global output. Due primarily to the high carbon intensity of electricity in China, the aluminium industry contributes around 5% of the country's total carbon emissions. On the efficiency front, China has made remarkable progress to lower the electricity consumption (alternate current) per tonne of electrolytic aluminium to 13 543 kWh – on par with the global best practice. Such progress is also attributable to the relatively young age of production facilities.

Figure 4 **Chinese industrial CO_2 emissions by sector, 2020-2050 (Reference case)**



- **Ammonia and methanol:** China's ammonia industry has experienced an overcapacity challenge for years. In 2019, the country managed to curb its ammonia production to only two-thirds of the total 70 Mt capacity (CCR, 2020), accounting for around 26% of global production. Although the fertiliser market does not look promising for absorbing the idle capacity, due to policies on reducing nitrogen pollution caused by overuse of ammonia fertiliser (Chai *et al.*, 2019), other applications such as ammonia's use as a shipping fuel (if it can be produced with net zero carbon emissions) could increase future demand. This implies that the carbon footprint of producing ammonia in China should be greatly reduced, as most Chinese ammonia is produced from fossil fuels.

On methanol, China has also taken the lead in both global production and consumption (Statista, 2019). Given that methanol has many applications in producing other important chemicals, such as being an important intermediary for olefins production and a road fuel additive, its role is expected to become even more important in the future.

Use of coal in industry

The technologies deployed in Chinese industry are similar to global industry, with the exception of chemicals and petrochemicals, where a coal-based industry has developed in China in contrast to gas and oil domination elsewhere. Chinese capital stock is relatively new, the latest plants are generally large, and energy efficiency is generally high. Pockets of outdated capital stock remain, but policies are aimed at their closure.

The dominance of coal in Chinese industrial energy and non-energy use (*i.e.* its use as a feedstock) is the largest and most pressing issue today. Coal accounted for 59% of China's overall primary energy consumption in 2018, while industry consumed around 28% of the country's total coal consumption.

Notably, coal use for production of synthetic fuels and synthetic organic materials is growing rapidly, which has resulted in high growth in CO_2 emissions. Alternatives to the use of coal for these purposes are possible, especially the potential use of bioenergy and renewably produced hydrogen and e-fuels. Scaling up the use of alternatives to coal in industry will be key to decarbonising the sector, improving local air pollution and moving China to the forefront of advances in manufacturing.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Set a clear direction and ensure that progress can be measured**
   - Co-develop with industry and other stakeholders low-carbon strategies and roadmaps for each sector, particularly in the steel, chemical and cement industries. Such strategies should set sectoral decarbonisation targets, and outline the development pathways for green electricity, hydrogen, biomass and CCS and how these decarbonisation options could be used in different industrial sectors through sector coupling strategies and technologies. Effective roadmaps require an open and ongoing dialogue with industry stakeholders to ensure that the latest information is used and that there is buy-in to implement the findings.

- Establish carbon accounting systems for key energy-intensive industrial products by applying a life-cycle analysis approach, focusing particularly on embedded carbon. Chinese industry may consider joining international energy and CO_2 benchmarking initiatives to develop complementary systems.

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2. Reduce energy use through energy and resource efficiency and demand reduction

- Improve energy recovery and use in the industrial sector and continue to improve industrial energy efficiency to reduce energy consumption, and develop mandatory performance and efficiency requirements to cover all of industrial energy consumption and update the Industrial Green Development Plan (2016-2020).

- Explore ways to lower the demand for industrial products (steel, cement, plastics, chemicals, etc.) such as improving the use of industrial products, extending the service life of products, recycling related products and materials, and developing alternatives for industrial products.

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3. Transition away from coal use in industry and build knowledge on the use of renewables

- Build knowledge of and confidence in emerging low-carbon solutions (such as hydrogen-based direct iron reduction and the use of renewable feedstocks for chemical production) by establishing demonstration projects to showcase the performance of the innovative technologies and exchange of learning and experiences.

- Nurture the market growth for "green" products and continued to provide incentives for energy efficiency improvements in the industrial sectors; however, certification of green supply chains may be required.

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4. Consider the optimal locations for industrial production and importation of green commodities

- Explore the optimal locations for industrial production, including relocating to regions with abundant renewable energy resources but low existing demand for electricity.

- Consider imported green commodities such as bioplastics and direct reduced iron (DRI) pellets to be viable substitutes for fossil-based products (Gielen *et al.*, 2020). In the latter case importing DRI from iron ore exporting countries with low-cost renewables potential, rather than importing iron ore, could reduce China's iron processing emissions while maintaining the higher-value steel production in China.

2.12 Continuing to support technology RD&D and broader systemic innovation

Since 2013, China has increased its investment in clean energy research, development and deployment (RD&D) and has become the second largest public sector investor in this area behind the United States (although the EU and its members collectively invest more). China is an active member of the Mission Innovation initiative, co-leading a number of international collaborations on RD&D; at the United Nations climate talks in Paris in 2015, alongside other Mission Innovation members, it committed to doubling its RD&D investments within five years. Chinese public sector RD&D expenditure increased from USD 3.6 billion in 2016 to USD 6.1 billion in 2018, although investments dropped back to USD 5.5 billion in 2019 (MI, 2020).

International Energy Agency figures (IEA, 2020b), which use a slightly different classification, suggest that in 2019 China spent USD 7.9 billion on energy RD&D, but only 53% of that (USD 4.2 billion) was spent on clean energy, suggesting that almost half of the Chinese energy RD&D budget was spent on technologies that are not consistent with the country's carbon neutrality goals. By contrast, the energy RD&D budget of the EU as USD 8.8 billion in 2019, of which 97% was focused on clean energy (USD 8.5 billion). This imbalance needs to be addressed if China wishes to deliver its objectives and play a leading role in clean energy technologies.

For RD&D and innovation support as a whole, the 14th Five-Year Plan included the goal of increasing government investment at least 7% over the next five years. This means that total spending could reach an estimated 2.8% of GDP by 2025, up from an estimated 2.3% to 2.4% in 2020. By comparison, the United States spent 2.83% of its GDP on R&D in 2018 and the EU spent 2.18%. A larger share of that increased RD&D budget should be focused on clean energy solutions.

Support for technology RD&D needs to be linked to broader systemic innovation – that is, combining innovation in enabling technologies with innovations in business models, market design and system operations. Further, support for technology RD&D and systemic innovation is needed to ensure deep decarbonisation. While many of the solutions that are needed exist, many are not yet fully proven or are more expensive. Further innovation can increase performance, reduce cost, increase confidence and plug gaps.

In the power sector, China's innovation support mechanisms should focus on: key technologies for large-scale wind turbines and for the industrialisation of high-efficiency solar cells, high-efficiency heat collection, and grid connections and transmission. Innovation for the system integration of variable renewables should focus on enabling a large number of distributed renewable energy grid-connected systems, dispatch control technology, and planning and operation of power systems with high shares of renewables. Finally, a focus is needed on large-capacity energy storage technology and energy Internet technology, with interactive intelligent power consumption and demand response technologies. IRENA's *Innovation Landscape for a Renewable-Powered Future* report (IRENA, 2019a) and accompanying briefing documents provide a comprehensive overview of the systemic solutions that can enable that transformation.

In the transport sector, road freight priorities include: designs of electric and fuel cell vehicles, research on batteries with high performance and low cost, hydrogen, synthetic fuels, and biofuels production and supply. For aviation and shipping, priorities for China should include: sustainable production of biofuels, synthetic fuel production and applications, energy storage and innovative propulsion designs.

In the industrial sectors, China's innovation support mechanisms should focus on: bio-based or synthetic chemicals that can be used as substitutes for fossil-based chemicals; green steel-making technologies including hydrogen-based DRI technologies and technologies based on the blast furnace-basic oxygen furnace (BF-BOF) approach with CCUS; clinker alternatives; and carbon removal technologies.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Increase public sector investment in clean energy RD&D**
   Stop the nearly 50% of public sector energy RD&D spending that is currently focused on energy technologies and solutions that are not low carbon, and divert this spending to clean energy RD&D.

2. **Continue and expand China's leadership role in international RD&D collaboration**
   The scale of the challenges faced requires a degree of burden sharing. Chinese leadership in some areas of technology development can influence the global transition and can be informed by experience elsewhere. China should continue to play an active role in international RD&D collaborations such as Mission Innovation.

2.13 Deepening global engagement

The energy transition is a global effort and will require international co-operation. Learning best practices from other countries or regions can benefit China, and Chinese expertise can help shape global energy transition outlooks. International organisations play a crucial role in convening the diverse actors and helping countries understand what the transition means for them by providing an outside view, sharing knowledge and convening key countries and actors. As a large and influential country, China can promote further improvements in existing international frameworks under related UN provisions and other international rules.

RECOMMENDATIONS FOR CHINA TO EXPLORE INCLUDE:

1. **Be a visible leader in international processes**
   - Continue to actively participate in both global energy governance and global climate governance, and strengthen China's participation in global and regional co-operation mechanisms and international bodies.

- Establish strategic partnerships with other major economies to shape the global transition of key sectors. A small number of major economies working in alignment could put key sectors such as steel and shipping on new pathways towards carbon neutrality. Priorities for deeper co-operation should include: international trade rules and their impact on carbon intensity of products, green financing and innovation.

2. Showcase China's successes

- Become a major provider of a full range of system solutions for carbon neutrality for other developing economies, using Chinese equipment manufacturing capabilities coupled with China's leading role in emerging digital technologies to provide a full range of low-carbon options.

- Further develop the International Forum on Energy Transition in Suzhou city into an international decarbonisation forum that convenes global actors to accelerate progress and that showcases China's leading role in those efforts.

CHAPTER 3
CONCLUSIONS AND AREAS FOR FURTHER WORK

China's announcement that it is aiming for a peak in CO_2 emissions before 2030 and to achieve carbon neutrality by 2060 has profound implications for how the country will consume energy and produce goods. Delivering on those objectives in just 40 years is a huge undertaking, and while many of the building blocks exist, many uncertainties on the optimal path remain. Substantial analysis and co-ordinated effort will be needed in the next few years to shape a robust path to 2060. It will be critical therefore to use the 2020s as a decade of planning, preparation and learning to gather evidence, make choices and address the enabling conditions necessary to build a new modern energy system for China.

China has many strengths, and some unique challenges, that will impact the pathway it takes. However, China is also not alone in striving to reach a net zero goal, as most major economies are now embarking on a similar journey. While China's energy transition is unique, it will share many common features with others, so the opportunities for mutual learning are large. Closer collaboration on multiple fronts will be essential for the success of all.

IRENA, in its role as the inter-governmental body for global energy transition, can support China in both learning from others and sharing Chinese experience with the world. This paper provides some key insights based on IRENA's work with countries around the world and on its analysis of global and regional energy transitions.

The paper provides high-level thinking on many complex topics. It can serve as a starting point to identify priorities for further deeper analysis. Thirteen priorities for stronger action have been highlighted, together with some initial recommendations. Each of these, however, warrants further deeper analysis on the specifics of China's energy transition, and consideration of the differences with transitions elsewhere to allow stronger conclusions to be drawn and more tailored recommendations to be developed.

Topics where significant uncertainties remain, and where China can particularly both benefit from and contribute to global action, include: the strengthening of power systems to integrate high shares of variable renewables, the expansion of electrification, and the decarbonisation of end-use sectors, specifically buildings, transport (particularly long-haul aviation and shipping) and industrial processes (particularly steel, cement and petrochemicals).

Closer collaboration between IRENA and relevant Chinese institutions, and discussions with Chinese policy makers, would help maximise the value of that work for China and for the world.

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