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Energy Security in the Context of Energy Transition – Lessons and Challenges within Europe and within China

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EU-China Energy Cooperation Platform was launched on 15 May 2019, to support the implementation of activities announced in the 'Joint Statement on the Implementation of EU-China Energy Cooperation'. The overall objective of ECECP is to enhance EU-China cooperation on energy. In line with the EU's Green Deal, Energy Union, the Clean Energy for all Europeans Package, the Paris Agreement on Climate Change and the EU's Global Strategy, this enhanced cooperation will help increase mutual trust and understanding between EU and China and contribute to a global transition towards clean energy on the basis of a common vision of a sustainable, reliable and secure energy system. Phase II of ECECP is implemented by a consortium led by ICF, and with National Development and Reform Commission - Energy Research Institute.

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Executive summary

With the adoption of the Paris Agreement in 2015, world leaders emphasized the need to limit global warming to 1.5°C by the end of the century to curb the negative effects of climate change. China aims to peak CO_2 emissions before 2030 and achieve carbon neutrality by 2060. The EU has a binding goal to be climate neutral by 2050. Achieving these targets requires a major overhaul of energy systems, including infrastructure, planning, and regulation, and coordinated progress across energy sectors. This means that for the coming decades, energy systems around the world are in transition. This transitional stage with a growing share of variable renewable energy (VRE) resources and technological uncertainties brings about new risks and the need for a redefinition of the concept of energy security.

This report aims to strengthen the understanding of energy security in China and EU in the context of energy transition. Through the collaboration between EU and China experts, a refined understanding of the energy security issues that each other's energy systems will face in the future was developed, because a detailed understanding of the specific risks surrounding the ongoing transition, including quantitative metrics to assess these risks and measures to mitigate them is needed. The co-existence of the fossil-fuel dominated system of the present and the emerging carbon-neutral system of the future creates tensions between two rather differing operational paradigms. China and the EU, with their ambitious carbon neutrality targets for 2060 and 2050 respectively, face similar yet not the same energy security challenges in the next decades of transition.

This report is the final report of the ECECP project: 'B2.4e Energy security in the Context of energy transition– Lessons and Challenges within Europe and within China'. The project kicked off on 24 August 2023 and ended in November 2023. The project partners are CEC (China Electricity Council), DEA, and Ea Energy Analyses.

This first part of this report explores the concept of energy security in China and the EU, and how the concept is changing in the energy transition. The second part of the report (WP2) quantitatively assesses the risks of being dependent on future (2050 and 2060) large scale variable renewables in the power system. The risks are associated with increased dependency on climate and weather patterns, e.g. wind, and solar power. This is done by a comparative analysis of the power system adequacy contribution (or load carrying capacity) of RE resources deployed in Europe vis-a-vis China; essentially comparing the degree to which RE-resources themselves will contribute towards maintaining generation adequacy, relative to projected demands.

China's perspective on energy security

China's energy security concerns align with the principles outlined in the 'New Energy Security Strategy,' emphasizing the following key points:

- **Enhancing Energy Efficiency:** The first priority is to drive an energy consumption revolution by reducing inefficiencies in energy use.
- **Diversifying Energy Supply:** The second objective is to promote a revolution in energy supply, fostering a diversified supply system.
- **Advancing Energy Technology:** The third aspect focuses on advancing energy technology to facilitate industrial upgrading.
- **Transforming Energy Systems:** The fourth goal involves revolutionizing energy systems, opening up a fast lane for energy development.

- **Global Energy Cooperation:** Finally, there is a commitment to strengthening international cooperation to ensure energy security within an open environment.

The EU’s perspective on energy security

The EU's energy security concept underscores cooperation and solidarity among Member States and regional partners. Cross-border cooperation, inter-connections and a functioning electricity market ensure that electricity can flow between Member States and partner countries and that the different countries can rely on each other.

The energy crisis triggered by Russia’s invasion of Ukraine has accelerated renewable energy deployment in the European Union, driving the bloc to urgently reduce its dependence on Russian natural gas imports. In May 2020, the European Commission proposed the ‘RePowerEU Plan’, with three main components: energy conservation, increased clean energy and diversifying energy supplies. This strategic response addresses the short- to medium-term energy crisis while accelerating the energy transition to reach the long-term decarbonisation targets.

Transitioning to Net-Zero Carbon: Navigating Energy Security Risks

A more global overview of energy security risks during transition is presented, ranging from fuel dependence risk and electricity system risks to cybersecurity risk and geopolitical risks. Each of the risks highlights the complex challenges and considerations involved in transitioning to a cleaner energy system.

For six risks that were particularly relevant for both China and the EU, suggested mitigation measures are derived, as summarised in the table below.

Table 0.1: Key Risks and Mitigation Measures in China and the EU

Risk	Mitigation measures China	Mitigation measures EU
Dependence on imported fuels	Increasing cooperation with foreign suppliers. Diversifying the import between different exporting countries. Consolidating internal supply chains for the development of synthetic fuels. Committing to a decarbonisation pathway involving renewables with a strong track record of scaling up renewable energy capacity.	Continue the strategy of diversifying the import between different exporting countries. Committing to a decarbonisation pathway involving renewables with a strong track record of scaling up renewable energy capacity.
Dependence of clean energy technologies on critical materials	Increase efforts to surveying and exploring the availability of critical materials in China. Direct investment in overseas sources of critical materials.	Direct investment in overseas sources of critical materials. Expansion of the critical materials supply chain through the establishment of contracts and long-term agreements.

Table 0.1: Key Risks and Mitigation Measures in China and the EU

Risk	Mitigation measures China	Mitigation measures EU
	Expansion of the mid and downstream in the critical materials supply chains. Invest in the development of alternative technologies which reduce or avoid the need for critical raw materials.	Invest in the development of alternative technologies which reduce or avoid the need for critical raw materials.
Inflexible and inefficient demand	Adopt cost reflectiveness in all energy prices. Adopt a decisive initiative to measure and digitise energy consumption while creating measures to incentivise consumer awareness. Create incentive mechanisms for retrofit and technology substitution.	Further adopt cost reflectiveness in all energy pricing. Further adopt a decisive initiative to measure and digitise energy consumption while creating measures to incentivise consumer awareness. Create incentive mechanisms for retrofit and technology substitution.
Climate impacts on energy production (renewable and non-renewable)	Invest in power system flexibility. (e.g. transforming coal-fired plants in China to enhance the flexibility for whole electricity system Enhance sector coupling. Invest in adequate reserves of climate-resilient firm capacity. Invest in more flexible and market-integrated inter-provincial transmission. Invest in both short-term and seasonal energy storage technologies. Incentivise demand response.	Invest in power system flexibility Enhance sector coupling Invest in adequate reserves of climate-resilient firm capacity Invest in more flexible and market-integrated transmission including new interconnectors between countries Incentivise demand response.
Uncoordinated technology transition	Develop a phase-in and phase-out plan focusing on specific metrics. Prolong the use of existing energy infrastructure. Model the mid-transition and evaluate intermediate scenarios.	Develop a phase-in and phase-out plan focusing on specific metrics. Prolong the use of existing energy infrastructure.

Table 0.1: Key Risks and Mitigation Measures in China and the EU		
Risk	**Mitigation measures China**	**Mitigation measures EU**
	Synchronise scaling up green fuels and technologies with scaling down fossil infrastructure.	Model the mid-transition and evaluate intermediate scenarios. Synchronise scaling up green fuels and technologies with scaling down fossil infrastructure.
Insufficient transmission system integration	Integrate the transmission system into the market mechanism, for example through implicit capacity auction in the market coupling mechanism. Integrated generation-transmission planning. Adopt socialised cost recovery mechanism More flexible inter-provincial transmission, which can adapt to the seasonal characteristics of resources in different regions. Accelerate the development of energy storage. Expand cross-regional infrastructure to transmit renewable power, pursuing transmission rescheduling, netting supply-demand imbalances and expanding resource-sharing areas.	Build new infrastructure/expand existing transmission where profitable (benefits >costs) Adopting socialised cost recovery mechanism in countries where this is not applied Adopt CBCA (cross border cost allocation) as a method to cost sharing Better utilise existing capacity (e.g. dynamic line rating) Integrated generation-transmission planning Accelerate the development of energy storage

Similarities and disparities between China and the EU were found as follows:

- Regarding dependency of imported fuels, the risk is assumed to decrease over time in both China and the EU. Both have officially declared that they follow and are currently implementing the transition track of large-scale deployment of renewables, especially PV and wind.
- When it comes to dependency of clean energy technologies on critical materials, China holds a global leadership position in most technology and critical material supply chains. Conversely, the EU relies on global trade and the establishment of long-term agreements and contracts. In order to mitigate this dependency and enhance environmental sustainability, the EU has heightened its emphasis on the recycling of critical materials.
- Inflexible and inefficient demand. In Europe, markets have been implemented in the energy sector during the last two-three decades. Recently also national plans for smart meter roll out to end-consumers have been implemented. That means

that many end-consumers are already able to react to energy prices and consume less when prices are high. The pass-through mechanism for prices from generation to end-consumers is so far more developed compared to China.

- Climate impacts on energy production. It is foreseen that climate impacts may affect the overall energy system in both China and the EU regardless of the technology choice towards carbon neutrality. The risks and mitigation measures have the same character.
- The risk of uncoordinated technology transition is more or less the same in China and EU. So are the proposed metrics and mitigation measures.
- *Insufficient transmission* system is a potential barrier for the green transition with large scale deployment of renewables, especially solar and wind. Europe has an established planning regime for power transmission which includes sector coupling with the natural gas sector and the hydrogen sector. The planning is done within the European market framework and based on Cost Benefit analyses. When China adopts a fully-fledged market approach, including a spot market, the transmission development in China can be market led and more efficient.

Quantitative weather impacts on energy production

The second part of the report (WP2/Chapter 4) quantitatively assesses the risks of being dependent on future (2050 and 2060) large scale variable renewables in the power system. The starting point for this study is the EU in 2050 and China in 2060 - we assume that, in accordance with the net zero targets, both electricity systems are fully decarbonised, and a correspondingly high proportion of the electricity capacity is covered by VRE resources. The assessment is based on regional weather data for European countries and Chinese provinces for a 20-year period (2000-2019). Essentially, the analysis is carried out by comparing the degree to which VRE resources contribute towards maintaining generation adequacy, relative to projected demands and taking changing weather patterns into account. The risks are associated with increased dependency on climate and weather patterns, e.g. wind, and solar power.

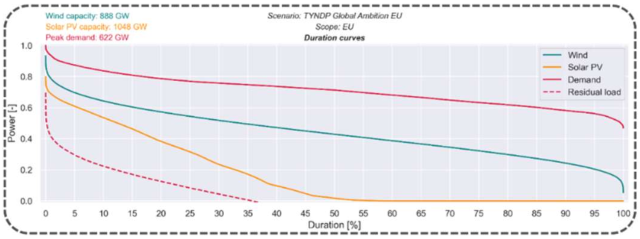
The scenario data for China 2060 is provided by the CEC and the CETO project. The EU scenario data corresponds to ENTSO-E's TYNDP 2050 Global Ambition Scenario and Distributed Energy scenario.

Key concepts of the quantitative assessment on weather impacts on energy production

Residual load

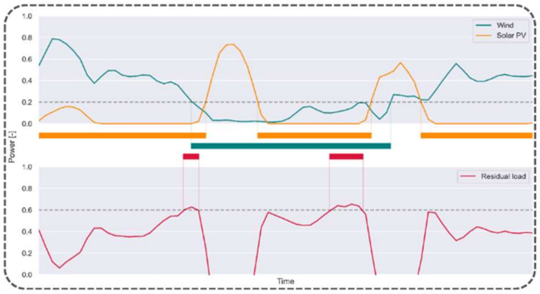
Residual load is a measure of the difference between demand and VRE generation. It can be a positive value when demand exceeds VRE generation (energy deficit) or it can be a negative value when VRE generation exceeds demand (energy surplus).

Duration curve



A *duration curve* is a statistical measure that shows how long a certain power is maintained in a power system. It gives an overview of the demand, wind and solar resources and VRE adequacy. In our study, duration curves are based on all the time steps utilising the full 20 years (2000-2019) of weather data.

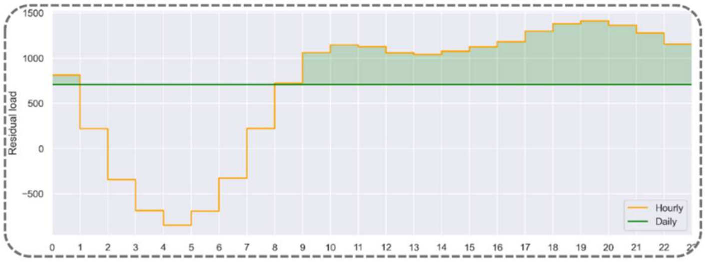
Energy droughts



An *energy drought* event is defined as a period of time where VRE generation is below a certain threshold or residual load is above a certain threshold in all time steps. This leads to a situation where the power system is at risk due to inadequacy for a prolonged period of time.

Flexibility needs

Flexibility needs are defined as the amount of energy that must be ‘shifted around’ to balance the residual load within a certain time scale (green area in the figure). In this report, we look at flexibility needs of a day, a week, and a year.



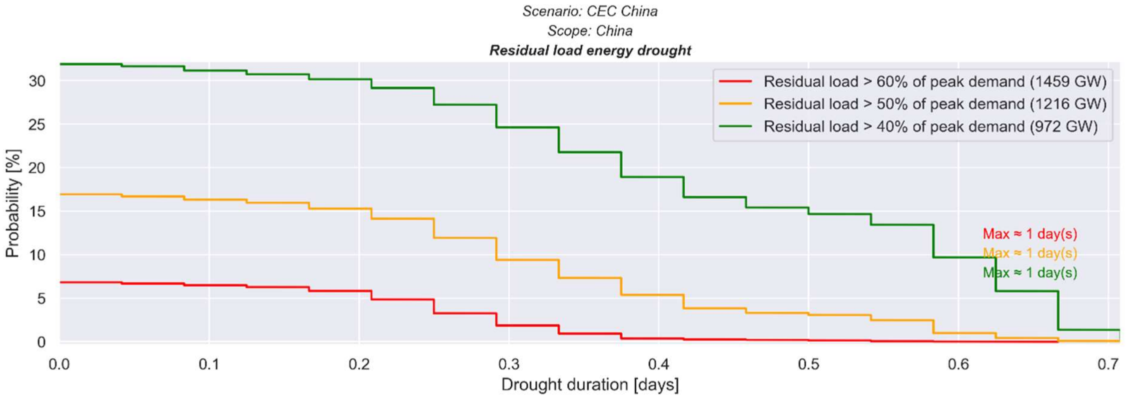
Two levels of analysis

The analyses are conducted at two levels: regional and total power system. At the regional level, individual countries or provinces (EU countries and Chinese provinces) are considered independently, accounting for local energy production and consumption with no transmission to neighbouring areas, while assuming no transmission bottlenecks within the regions. At the total power system level, the power per timestep is aggregated across all EU countries and Chinese provinces, assuming no transmission bottlenecks within and between regions.

Findings from the quantitative assessment of weather impacts on energy production

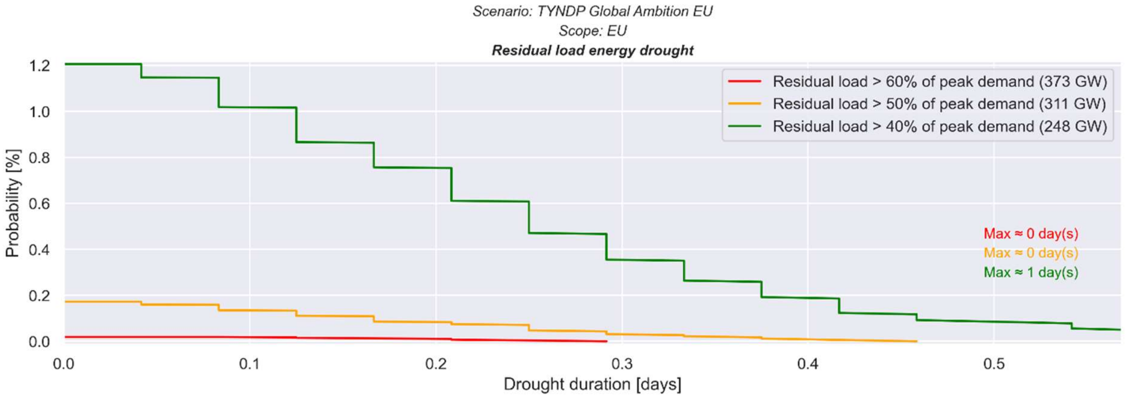
- Rapidly adjustable flexible energy sources are valuable in filling the gaps left by VRE, potentially reducing the need for long-term baseload capacity during periods of low wind or solar generation and high demand.
- The risk of energy droughts arises when low generation coincides with high demand over an extended period, posing a challenge to the power system's balance between supply and demand.
- The analyses reveal that residual load droughts are generally short, lasting less than a day, in both China and the EU, with China experiencing more frequent events due to lower VRE generation coverage.
- The daily demand pattern helps mitigate the impact of wind and solar droughts by breaking them into shorter periods.

Figure 0.1: Residual load energy drought



Source: CEC China 2060 scenario.

Figure 0.2: Residual load energy drought



Source: TYNDP GA EU 2050 scenario.

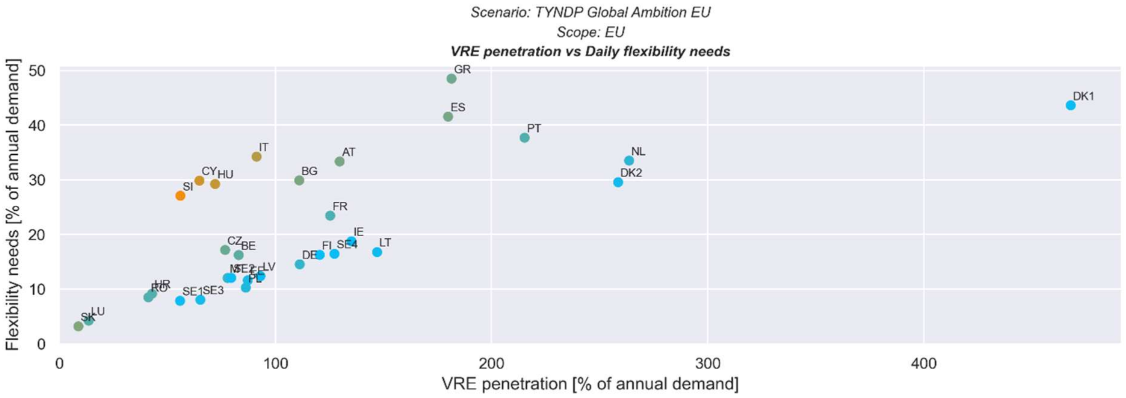
Note: Figure 0.1 and Figure 0.2 show the residual load energy drought for the CEC China 2060 and the TYNDP EU 2050 Global Ambitions scenario, showing the probability of cases where generation from wind and solar is low at a time where residual load is above a certain threshold (40%/50%/60%). It's important to note that these findings are based on the total power system level for both China and the EU, and results may differ significantly at the country or province level. The variation for the total power system is smaller than most of the regional variability, which shows that deviations as expected tend to smoothen when considering larger geographies.

Solar droughts are generally lasting longer in EU countries (higher seasonal impact), while China is experiencing longer durations of wind energy droughts.

- There are significant regional variations in the maximum durations of energy droughts in both China and the EU, with solar droughts generally lasting longer in EU countries due to factors like higher latitudes leading to longer nights in winter, aligning with the broader comparison of China and the EU at the total power system level; furthermore, prolonged residual load droughts in places like Beijing, Shanghai, Sichuan, and Slovakia primarily result from high demand exceeding VRE capacities.

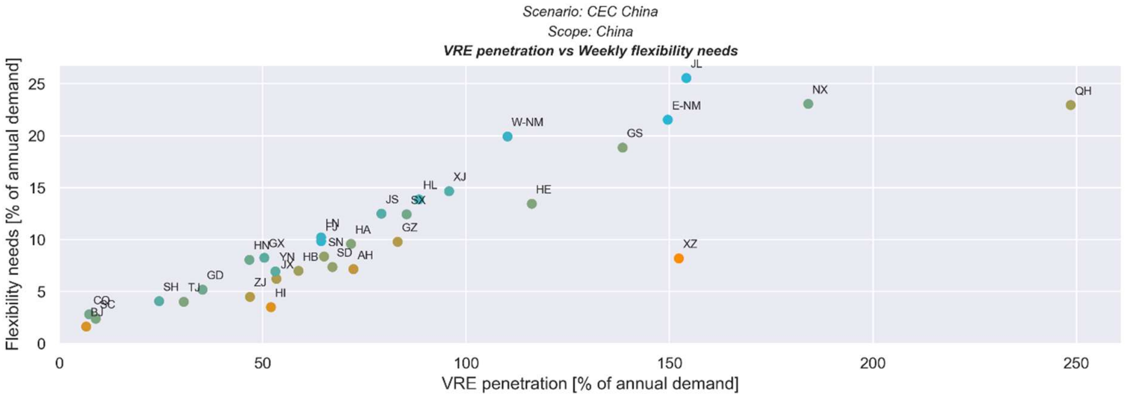
- In both China and the EU, wind energy droughts range from a few days to several weeks, with China experiencing longer durations. China's severe wind droughts can last up to 5 days with generation falling below 20% capacity, and up to 58 days below 40% capacity, compared to the EU's 4 days and 17 days, respectively.
- Solar PV duration curves are similar in both regions, but droughts tend to be shorter in China than in the EU. In China, short solar droughts, lasting less than a day, are common due to the daily pattern of sunrise and sunset, while long-term droughts caused by seasonality and overcast skies are unlikely to occur simultaneously across the entire country. In the EU, solar droughts also follow a daily pattern, but they can last longer, particularly due to factors like longer nights in winter, although most severe events are still typically short-term.

Figure 0.3: EU VRE penetration vs. daily flexibility needs



Source: TYNDP GA EU 2050 scenario.

Figure 0.4: China VRE penetration vs. weekly flexibility needs



Source: CEC China 2060 scenario.

Note: Yellow dots represent provinces where VRE is dominated by PV; blue dots represent provinces where wind is dominating.

The main need for flexibility in the VRE dominated power systems in both the EU and China relates to achieving daily balancing of the power system between hours.

- Flexibility needs are most significant for daily balancing in VRE-dominated power systems in both the EU and China.
- Among the considered time scales (daily, weekly, and annual), addressing daily fluctuations in energy generation and consumption requires the highest level of flexibility.
- Short-term flexibility requirements are less affected by year-to-year weather variations compared to long-term needs, which are influenced by seasonal changes.
- Solutions for flexibility needs will vary depending on the time scale, with short-term flexibility achievable through batteries or quickly adjustable energy sources, while long-term flexibility is better addressed through technologies like pumped hydro.
- Regions with a higher proportion of solar PV in VRE generation will generally have greater daily flexibility needs, while regions with a higher share of wind energy will require more flexibility on a weekly basis, aligning with the durations of solar and wind energy droughts.

A capacity remuneration mechanism could ensure power adequacy in the few hours of peak load.

- In China (CEC scenario), VRE meets 25% of demand continuously, while in the EU (TYNDP Global Ambition scenario), it covers around 65% due to higher VRE generation coverage.
- Both regions exhibit steep residual load curves with high peaks even in areas with significant VRE penetration, indicating a need for substantial backup capacity.
- To ensure power adequacy at all times, a separate mechanism for the remuneration of capacity, involving generators, electrical storage, demand reductions, and interconnector imports, may be a solution, as relying solely on the spot market may not incentivise backup power investment.

Power industry approach to energy system transition

The report highlights a notable aspect: a positive approach within the power industry toward the energy transition in both China and the European Union. For China, these include China Huaneng Group Co., Ltd., and China Datang Group, and for Europe Ørsted (Denmark) and RWE (Germany).

Mitigating Energy Security Risks: Lessons from the EU and China

Both the EU and China offer valuable insights in handling specific energy security threats and managing related risks.

Lessons from the EU

Lesson E1: Diversification of supply, aggregation of demand and a market correction mechanism

The key lesson learned is the importance of diversifying natural gas supply sources to reduce dependency on a single supplier, as demonstrated by the EU's response to the reduction in Russian natural gas imports by increasing LNG-imports and natural gas supplies from other countries and implementing mechanisms like 'AggregateEU' for demand aggregation and joint gas purchases, along with a short-time market correction mechanism to address extraordinarily high prices during times of scarcity.

Lesson E2: Emergency intervention and long-term market reform

While the current electricity market design was not to blame for the energy crisis, it helped mitigate its impact. Interfering heavily with liberal market price signals could jeopardise the benefits achieved over the years. To address surging electricity prices, the EU introduced an short-term inframarginal generator market revenue cap, ensuring additional revenues are redistributed to consumers, with a focus on supporting renewables and reducing dependence on volatile fossil fuel prices in the long-term market reform (applied until June 2023).

Lessons from China

Lesson C1: Diversification of imported fuels is important for energy security

China has effectively diversified its fuel imports, including oil, gas, coal, and uranium, from various international sources, in addition to maintaining a domestic supply of these resources.

Lesson C2: Importance of diversification of supply of critical materials for energy system transformation

China plays a crucial role in the supply chains of clean energy technologies, giving it a strategic advantage in accessing critical materials for energy system transformation.

Lesson C3: Uncoordinated technology transition must be avoided

To mitigate risks, it is crucial to avoid an uncoordinated transition of technologies, as determining the optimal timing and progress can be challenging.

Lesson C4: Wholesale market price variations must be reflected in consumer prices

In the context of China’s energy transformation, in which market-oriented reform is embraced as a guiding principle, the risk for allowing parts of the system to operate under market conditions while others remain directly controlled increases the risk for the absence of flexibility and efficiency.

1. Introduction

This report is the final report of the ECECP project: B2.4e Energy security in the Context of energy transition– Lessons and Challenges within Europe and within China. While the concept of energy security has traditionally been strongly influenced by the oil crisis of the 1970s with its main focus on ensuring the demand for fossil fuels, fossil fuels will play only a negligible role in a net zero future.

Since there is still a long way to go to achieve a carbon neutral energy system, this report focuses on the concept of energy security in the transition phase. With the ongoing transformation of energy systems as background, the concept of energy security requires a re-assessment to identify the specific risks posed, the metrics to be assessed as well as the potential measures that help to mitigate these risks. This project aims to strengthen the understanding of energy security in EU and China in the context of energy transition. Through the collaboration between EU and China experts, a refined understanding of the energy security issues each other's energy systems will face in the future will be developed.

The project was launched on 24 August 2023 and is planned to be finalised in November 2023. The project partners are CEC (China Electricity Council), DEA, and Ea Energy Analyses.The project is divided into two work packages WP1 and WP2.

WP1 is a strategic approach to conceptualizing energy security during and post energy transition including among others:

- Access to, and dependence on fuels.
- Dependence on clean energy technologies and critical material supply chains.
- Consistency between markets, adequacy planning approaches, and policies during transition.
- Transitional risks in the power system

The remainder of this report is structured as follows:

Chapters 2-3 describe the outcome of WP1.

Chapter 2 is a general chapter on energy security, and security in context of energy transition, and China's and EU's perspectives on security

- Chapter 3 describes important components of energy security aspects during and post energy transition. A subset of main risk factors for the energy transition in China and the EU are given a more detailed evaluation.

Chapter 4 is the reporting of WP2. This WP includes a quantitative study elucidating:

- Security risks associated with increased dependency on climate and weather patterns, e.g. for wind, and solar power
- Comparative analysis of the power system adequacy contribution (or load carrying capacity) of RE resources deployed in Europe vis-a-vis China; essentially comparing the degree to which RE-resources themselves will contribute towards maintaining generation adequacy, relative to projected demands.

Chapter 5 describes important lessons learned on energy security in China and the EU.

Chapter 6 gives examples of power producers’ approach to the green transition in China and Europe.

Chapter 7 is the conclusion.

Chapter 8 is the Annex.

The Annex at the end of the report includes a list of abbreviations and references, as well as a list of Figures and Tables.

Please note: An additional Annex is downloadable on the ECECP website, containing regional results for different EU Member States and Chinese provinces.

2. Energy security – conceptualisation

2.1 A net-zero energy system

With the European Green Deal and China's 'dual carbon' targets, the governments of the EU and of China have pledged to decarbonise their economies, focusing first and foremost on their energy systems. The vision of a climate neutral Europe by 2050 and a carbon neutral China by 2060 is currently guiding new policies and investments. However, achieving these goals is a challenging task.

How will the world look when the net-zero emissions target is reached by 2050 in the EU and by 2060 in China? The 'target' model is an energy system in which renewables are the main supply source, many energy services are electrified, and a variety of flexibility and storage solutions are available. Emissions in hard-to-abate sectors are captured by carbon capture technologies and otherwise separate systems are now integrated. Electricity markets with reliable price signals and interconnected grids enable the efficient allocation of energy resources.

There are different pathways to get to the 2050/2060 system of a net-zero emissions economy, accompanied by many uncertainties, such as the speed of technological innovation and technology uptake, openness to behavioural change and cooperation between countries, all of which are difficult to predict. For the coming decades, our energy systems will be in transition. This transitional stage, featuring a growing share of variable renewable energy (VRE) resources and technological uncertainties brings with it new risks and the need for a redefinition of the concept of *energy security*.

2.2 What is energy security?

Defining and measuring energy security is a multi-dimensional and sometimes elusive endeavour, as is acknowledged by many authors and sources. Historically, the concept of energy security has been associated with the availability and affordability of fossil fuel supplies – notably, crude oil. In fact, the International Energy Agency (IEA), which importing countries established in 1974 in response to the oil crisis of the time, defines energy security as the uninterrupted availability of energy sources at an affordable price (IEA, 2023d, 2023e).

However, the IEA has long recognised the need to adapt its understanding of energy security and with this in mind has introduced updates to its analytical framework. One example is the IEA model of short-term energy security (MOSES) which focuses on vulnerabilities that can last for days or weeks. Beyond oil, the framework encompasses the availability of renewable resources such as water and wind, the continuous and safe operation of infrastructure such as pipelines and transmission lines, and the resilience to shocks from the demand side (Jewell, 2011).

While energy security is a main energy policy objective, Winzer (2012) notes that it is defined imprecisely. To navigate the variety of existing definitions, Winzer categorises them according to the sources of risk, the scope of impacts caused and several subjective 'severity filters' such as the speed, size, sustention, sureness, and singularity of these impacts. Winzer recommends a definition of energy security as ‘the continuity of energy supplies relative to demand’.

Bielecki (2002), who suggests that energy security coexists and often competes with other public policy objectives such as economic development and environmental protection, indicates that ‘energy security is commonly defined as reliable and adequate supply of energy at reasonable prices’. Bielecki further points out that energy security has the characteristics of a public good, which is inadequately supported by market mechanisms. Like any public good, it is characterised by non-rivalry and non-excludability and thus its benefits are equally available to those who pay for it and to those who do not.

With a workable perspective in mind, Sovacool & Mukherjee (2011) suggest an analytical framework to analyse national energy security and performance, and propose a definition that comprehends five dimensions: availability, affordability, technology development, sustainability, and regulation. Their analysis further suggests breaking down these five dimensions into specific components which are ultimately categorised into 320 simple indicators and 52 complex indicators which scholars and policymakers can use to measure, analyse, and track energy security.

2.3 Energy security in the context of the energy transformation

The ongoing energy transition is bringing about a profound transformation of the energy system. Besides the challenge posed by the increased penetration of VRE sources such as wind and solar, otherwise separate systems are becoming integrated. For example, the production of green electricity is now expected to become the main fuel source of green hydrogen and other end use products in emerging supply chains known as Power-to-X (P2X). The capture, transport, and storage of CO_2 (CCS) is now feasible with large-scale projects now being implemented as part of society’s overall effort to lower emissions and reduce environmental impact.

This overarching transformation requires a fresh assessment of what is meant by energy security. Policymakers need a detailed understanding of the specific risks surrounding the ongoing transition, including quantitative metrics to assess these risks and measures in order to mitigate them. Governments and agencies are beginning to realise that future energy security cannot be evaluated on the basis of traditional supply chains and usage patterns, or by limiting the analysis to existing policies alone (SEAI, 2020).

2.4 Between ‘now’ and ‘then’: the concept of mid-transition

Apart from the risks, the transformation also creates opportunities to strengthen energy security, which bring with them the potential to reinforce competitiveness. Indigenous renewable energy production reduces dependence on fossil fuels, which are often imported, and ultimately diminishes the environmental impact of the energy sector.

However, between now and then – that is, between the present and the future, there are challenges that need to be addressed and risks that must be mitigated: the current system will differ substantially from the future, carbon-neutral reality.

The co-existence of the fossil-fuel dominated system of the present and the emerging carbon-neutral system of the future creates tensions between two rather different operational paradigms which – among other things – impact infrastructure requirements.

Grubert & Hastings-Simon (2022) refer to this period, during which the existing and future systems impose constraints on each other, as the 'mid-transition'. During this period, the main objective of the energy system is to reduce greenhouse gas emissions, but both fossil carbon-emitting systems and zero-carbon systems coexist at a scale that has a significant impact on them. As defined by Grubert & Hastings-Simon, the mid-transition is a period between two stable end points during which change is directional and coexisting systems must make compromises to accommodate the other.

Further, the mid-transition is characterised by an increasing risk arising from failure to spot synergies and uncoordinated decision making, making trade-offs more evident and more necessary. For example, higher shares of VRE in the system increase the need for balancing services which secure the stable operation of the power system. However, these are typically supplied by fossil generators whose profitability is reduced as renewables achieve higher shares of production, and carbon-emitting technologies, which operate fewer hours, are phased out.

Another example of such trade-offs is evident in the tensions arising between traditional and electricity-based transportation systems. As the electrification of transportation gains momentum, fossil fuel distribution networks will become less economically viable. Similarly, the broad penetration of electric vehicles requires network reinforcements, which will ultimately be financed by all electricity consumers even if many of these continue to drive fossil fuel vehicles.

From a policy perspective, the mid-transition will require interventions in which explicit and coordinated plans account for both the phase-in of zero-carbon technologies as well as the phase-out of carbon emitting technologies. It is important to identify cut-off metrics that determine when systems are constraining each other. As a rule of thumb, Grubert & Hastings-Simon suggest that the period during which between 20% and 80% of energy is supplied by variable energy renewables may be an indication of the mid-transition.

However, further refinements to this concept may be required, as a variety of technical, economic, and institutional factors may help determine the mutual constraints imposed by both kinds of technologies, leading to asymmetric impacts. For example, a system with 30% VRE penetration may impose stronger constraints than a system with more than 50% penetration, if the one with lower penetration is characterised by lack of flexibility, and/or fewer technological solutions or market mechanisms that facilitate the integration of renewables. In addition, the mid-transition raises a variety of justice, equity and environmental considerations that must be addressed in policy considerations.

2.5 The IEA's renewed perspective on energy security during the energy transition

In its most recent World Energy Outlook (WEO23), the IEA highlighted the need for a reassessment of energy security in the context of the energy transition, stating that fossil fuel markets remain tense and volatile despite a decrease in prices from 2022 peaks, while geopolitical tensions persist in regions like Ukraine and the Middle East; additionally, the global economy is challenged by factors like inflation, higher borrowing costs, and increased debt levels, while urgent action is needed to address climate change and air pollution linked to the energy sector (IEA, 2023c). This broader, more holistic perspective on energy security responds to the mandate issued by the IEA Governing Board to include issues beyond oil, natural gas and electricity – thus expanding the focus of energy security to include renewables, zero emissions transport, greenhouse gas abatement technologies, as well as heating, cooling, energy efficiency, and critical minerals and materials (IEA, 2022d).

Among the issues identified in WEO22 is the trade-off between short-term benefits and long-term emission reduction goals. As an example, the German government recently decided to temporarily prolong coal-fired generation and has permitted the short-term expansion of the Luetzerath coal mine, as part of its efforts to reduce gas demand and thereby tackle the ongoing energy crisis. According to RWE, the agreement could bring forward the generator's phase out of coal by eight years (RWE AG, 2022, 2023).

WEO22 also reflects on the interaction between high fossil fuel prices and the transition to clean energy technologies (IEA, 2023b). Although a high fossil fuel price environment should - in principle - improve the economic case for the transition, short-term volatility could delay the transition even further. In WEO22, the IEA notes that the oil price increase between 2021 and the first six months of 2022 is equivalent to USD 70 per tonne of CO_2 price on oil use and that the natural gas price increase seen in Europe over the same period is equivalent to USD 350/t CO_2.

However, the short-term effect of this price volatility could instead mean that pressure arising from high fossil fuel import bills may divert financial resources from clean energy investments to fossil fuel subsidies intended to shield consumers from temporary volatility. Therefore, moves to ensure that critical, traditional energy sources remain available during the transition to clean energy technologies are vital to ensure a smoother transition.

Similarly, the IEA emphasises that although the future, sustainable energy system brings inherent energy security benefits, there will be new energy security risks that reflect the realities of the new sustainable energy future. It is one of the main objectives of this study to investigate some of these risks in the context of the energy transformation in China and Europe, and to provide an assessment of the impacts of these risks.

2.6 China's perspective on energy security

China has taken decisive steps towards its long-term energy system transition, and a variety of indicators evidence the progress achieved so far. In 2021, non-fossil power generation capacity exceeded coal-fired power generation for the first time. In addition, during the period 2012-21 the share of coal in total consumption has decreased 12.5 percentage points - from 68.5% in 2012 to 56% in 2021, while in the period 2013-21 clean energy consumption has risen 10 percentage points – from 15.5% in 2013 to 25.5% in 2021.

China's five-in-one approach laid out in 2012, which comprehends economic, political, cultural, social, and not least construction of an 'ecological civilization' is the foundation of the country's ongoing transformation. According to this approach, sustainability must be a guiding principle in China's future development. Further, Chinese policymakers recognise that the interaction between the narrower concept of resource security and the broader definition of energy security has direct interlinkages with economic and social security, as well as with the strategic goal of constructing ecological civilization.

A more specific energy security strategy was outlined in the 'Four Revolutions, One Cooperation'[1] concept from 2012. This strategy, which proposed far-reaching reforms in energy consumption, energy supply, energy technology and energy systems, together with international cooperation, has shaped the energy agenda of the past decade.

While several aspects of the 'Four Revolutions, One Cooperation' strategy are worth highlighting, it is China's decisive embrace of market-based mechanisms that perhaps requires the most attention. Looking forward to the country's transformation of its energy system, China is committed to letting markets determine the allocation of energy resources, while securing appropriate regulation and state intervention that provides adequate institutional certainty. The establishment of national electricity and carbon markets is a clear indication of this commitment. Furthermore, China's adoption of the dual carbon target, which establishes an explicit goal of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, represents a clear commitment by Chinese policymakers to China's energy transformation.

China's line on energy security and how this is evolving in the context of the energy transition

As an emerging economy and the 'world factory' with growing energy demand, China has always been cautious about energy security. Ensuring adequate energy supply and energy conservation have been central to energy security in China.

Like Europe, China lacks its own oil and natural gas resources, leaving it highly dependent on imports. But unlike Europe, energy demand in China is growing rapidly, and it is therefore difficult to plan for supply to meet demand at all times. Therefore, energy planning in China commonly incorporates large supply margins.

Traditionally, energy security tends to be focused on oil and natural gas. However, with the deployment of renewable energy, the main focus of energy security has been evolving, and energy security has expanded to include other energy sources.

The development of renewable energy makes the energy system less dependent on fossil fuels and inherently safer. However, the path towards net zero is full of uncertainties. Solar and wind energy resources are relatively evenly distributed around the world, and critical minerals required for renewable energy equipment have much higher recoverability than fossil energy. The development of renewable energy means that energy security is gradually shedding its strong dependence on resources and is turning towards dependence on technologies.

The past few years have witnessed the positive impact of technological innovation on energy security in both Europe and China. However, during the first round of deployment of renewable energy, every country will face the challenge of how to ensure the stability and security of energy systems while vigorously developing intermittent renewable energy. In addition, renewable energy equipment as well as the associated critical minerals required are becoming politically sensitive as the market expands.

As the world transitions away from traditional fossil energy and towards renewable energy, the inherent risks of the energy system are compounded by ever-changing international environmental impacts and effects of extreme weather events. The security

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[1] 'China's energy in the new era is advancing bravely on the road of high-quality development,' National Energy Administration, 31 Dec 2020 (http://www.nea.gov.cn/2020- 12/31/c_139631430.htm). Strategy of 'four revolutions, one cooperation' ('四个革命、一个合作') for energy security, based on instructions from General Secretary Xi Jinping at the 18th National Congress of Communist Party of China in 2012.

risks of energy become highly complex. In the last few years, factors like the COVID-19 pandemic, global climate change, the Russia-Ukraine conflict, and changes in the global geopolitical pattern have led to a sharp rise in fossil fuel prices, which have in turn pushed up electricity prices, leading to high inflation and curbing global economic growth. These events have prompted the governments of several countries to rethink the energy transition pathway, and to place a higher value on energy security.

The energy 'trilemma', namely affordability, security-of-supply, and low-carbon, has to be properly handled during the energy transition. Firstly, less investment in the fossil fuels results in a fragile supply-demand balance. Global fossil fuel prices will be more sensitive to the impact of traditional factors such as international security situation, energy geopolitics, and capital speculations. Secondly, the intermittency of renewable energy, together with extreme weather events, have been impacting the safe and stable operation of the power industry. Negative prices have become more frequent in almost all major countries, indicating insufficient flexible resources in those power systems. Thirdly, the supply chains for renewable generation equipment as well as grid connections are buckling under the strain imposed by rapidly accelerating installation targets. The fast-growing renewable energy market has led to wildly fluctuating production capacity as well as price volatility for key components as well as raw materials. Queuing up for grid connections happens not only in China, but also in the US and some European countries.

The electricity market reform that is under way makes it more difficult to estimate the risks of energy security in China. On one hand, price signals are not as effective as in Europe to guide investments in renewable energy and flexible sources. On the other hand, modification of market rules could trigger significant market failures when the market encounters other shocks. Therefore, the pace of market reform and associated aspects of the energy transition needs to be weighed against a variety of factors, such as fossil fuel prices, the balance of supply and demand, the acceptance of electricity customers, etc.

In general, China's concerns on energy security are still summed up by the arguments made in the 'New Energy Security Strategy', including 'Four Revolutions and One Cooperation'. China's New Energy Security Strategy emphasises the synergy between production and consumption, the fundamental role of technology, global energy cooperation, and energy security in an open environment:

- Firstly, promote the energy consumption revolution and curb irrational energy consumption.
- Secondly, promote the energy supply revolution and establish a diversified supply system.
- Thirdly, promote the energy technology revolution and promote industrial upgrading.
- Fourthly, promote the energy system revolution and open up the fast lane for energy development.
- Fifthly, strengthen international cooperation to achieve energy security under open conditions.

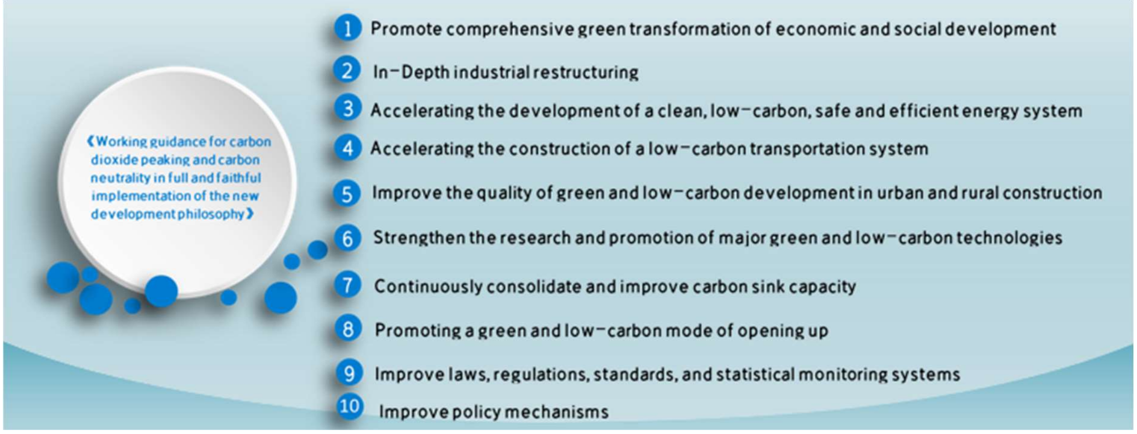
China's Blue Book

In September 2020, China updated its nationally-determined contribution targets which aim for CO_2 emissions to peak before 2030 and for carbon neutrality before 2060, giving

China a gap of about 30 years between the two targets. In comparison, the gap for the EU is 71 years[2], for the US 43 years and for Japan 37 years.

In October 2021, Chinese President Xi Jinping stated that China would ‘put in place a “1+N” policy framework for carbon peak and carbon neutrality’. ‘1’ refers to the long-term approach to combating climate change, which is well documented in ‘The Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy’, issued in October 2021 (see Figure 2.1), and in the ‘Action Plan for Carbon Dioxide Peaking Before 2030’, issued in October 2021 (see Figure 2.2). China aims gradually to increase the share of non-fossil energy consumption to around 20% by 2025, around 25% by 2030, and over 80% by 2060.

Figure 2.1: Ten aspects in working guidance for CO_2 peaking and CO_2 neutrality



《Working guidance for carbon dioxide peaking and carbon neutrality in full and faithful implementation of the new development philosophy》

1. Promote comprehensive green transformation of economic and social development
2. In-Depth industrial restructuring
3. Accelerating the development of a clean, low-carbon, safe and efficient energy system
4. Accelerating the construction of a low-carbon transportation system
5. Improve the quality of green and low-carbon development in urban and rural construction
6. Strengthen the research and promotion of major green and low-carbon technologies
7. Continuously consolidate and improve carbon sink capacity
8. Promoting a green and low-carbon mode of opening up
9. Improve laws, regulations, standards, and statistical monitoring systems
10. Improve policy mechanisms

Source: CEC.

‘N’ refers to specific implementation plans for key areas such as energy, industry, construction, and transport, and for key sectors such as coal, electricity, iron and steel, and cement, coupled with supporting measures in terms of science and technology, carbon sink, finance and taxation, and financial incentives.

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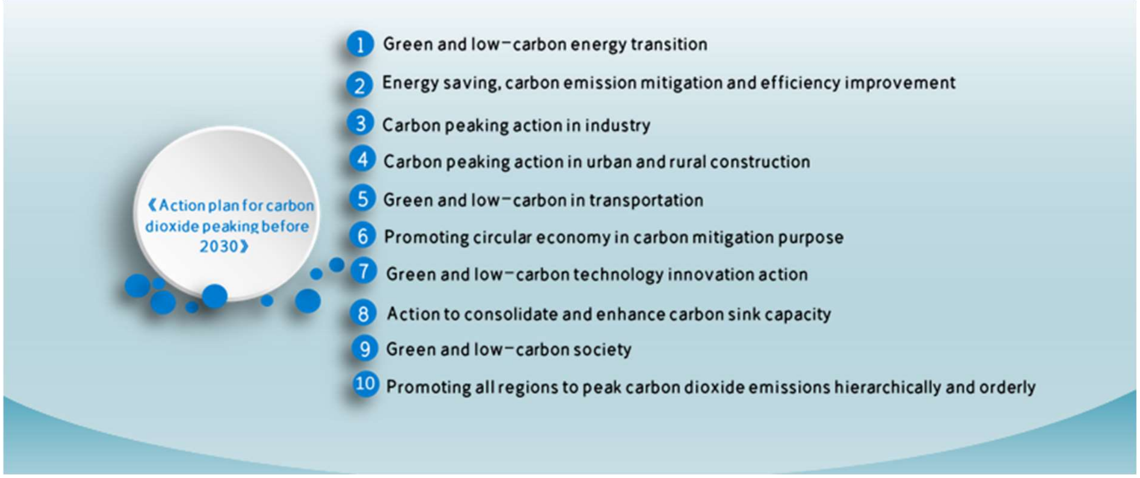
[2] The European Union produced approximately 2.73 billion tons of carbon dioxide emissions in 2022. The highest level of CO_2 emissions produced in the EU was in 1979, at 3.99 billion tons (Statista, 2023). The EU’s target is to be climate neutral by 2050.

Figure 2.2: Ten measures in the ‘Action plan for CO_2 peaking before 2030’



《Action plan for carbon dioxide peaking before 2030》

1. Green and low-carbon energy transition
2. Energy saving, carbon emission mitigation and efficiency improvement
3. Carbon peaking action in industry
4. Carbon peaking action in urban and rural construction
5. Green and low-carbon in transportation
6. Promoting circular economy in carbon mitigation purpose
7. Green and low-carbon technology innovation action
8. Action to consolidate and enhance carbon sink capacity
9. Green and low-carbon society
10. Promoting all regions to peak carbon dioxide emissions hierarchically and orderly

Source: CEC.

On 15 March 2021, President Xi Jinping offered important instructions on building a new power system at the ninth meeting of the Central Financial and Economic Commission. In the two top-level design policy documents mentioned above, a new electric power system is planned that includes an increasing share of new energy resources (renewables).

After seeking public opinions, the National Energy Administration released the ‘Blue Book for the Development of New Power Systems’ (hereinafter referred to as the ‘Blue Book’) in June 2023 (NEA, 2023). The Blue Book was jointly compiled by 11 research institutions and was coordinated by the National Energy Administration. It outlines the strategic direction for the transformation and development of the power industry, comprehensively helps promote the energy revolution, puts forward plans for a new energy system, and advocates green energy development (see Figure 2.3).

Figure 2.3: The Blue Book for the Development of New Power Systems

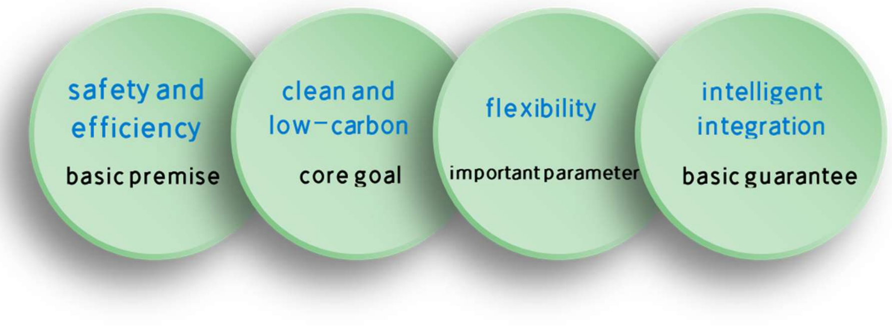
Press conference of the Blue Book on June 2nd, 2023

《Blue Book for the Development of New Power Systems》

Source: CEC.

The new power system has four important characteristics, namely safe and efficient operation; clean and low-carbon efficiency; flexibility; and intelligent integration, among which ‘safety and efficiency’ are the basic premise, ‘clean and low-carbon’ is the core goal, ‘flexibility’ is an important parameter, and ‘intelligent integration’ represents the basic guarantee. This is termed as the ‘four-in-one’ framework system of the new power system (see Figure 2.4).

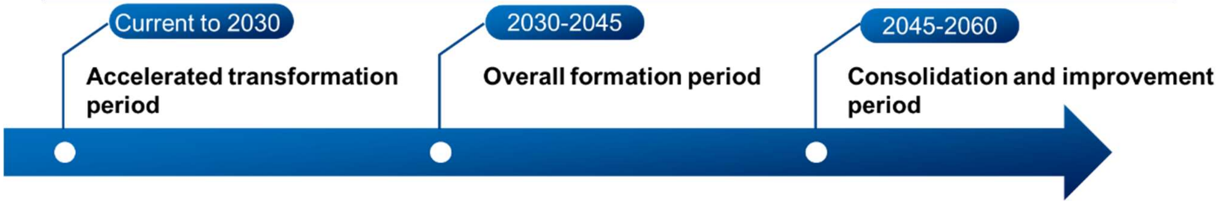
Figure 2.4: Four key characteristics of the new power system in the Blue Book



Source: NEA (2023).

The Blue Book proposes that in accordance with the 'two-step' strategic arrangement of the new era proposed by the Party Central Committee, the '2060 strategic goal' will be anchored, and 2030, 2045, and 2060 will be important milestones en route to the construction and formulation of a new power system (NEA, 2023). The 'three-step' development path of the system includes the accelerated transformation period (current to 2030), the overall formation period (2030–45), the consolidation and improvement period (2045–60), and the promotion of new electric power in planned and step-by-step stages (see Figure 2.5).

Figure 2.5: The 'three-step' development path of the new power system



Source: NEA (2023).

The Blue Book additionally makes it clear that the new power system relies on secure energy and power supplies. Its primary goal is to ensure power demand is met for high-quality economic and social developments, and its main task is to facilitate the construction of an energy supply and consumption system that includes a high-proportion of new energy.

In terms of the overall structure and key tasks, the Blue Book contains plans to strengthen the construction of four major systems: the power supply support system; the new energy development and utilisation system; the energy storage scale layout and application system; and a system to enable intelligent operation of the power-system. In addition, the Blue Book includes a strategy to develop three-dimensional basic support roles for the new power system, including standards and specifications, core technologies and major equipment, and relevant policies and institutional mechanism innovations.

2.7 Europe’s perspective on energy security

The European Green Deal

In December 2019, the European Commission presented the ‘European Green Deal’ (Green Deal), the EU’s vision to become climate neutral by 2050. The goal is to produce net-zero emissions of greenhouse gases by 2050 and to decouple economic growth from resource use while leaving no person and no place behind (European Commission, 2023d). The Green Deal covers all sectors of the economy, notably transport, energy, agriculture, buildings, and industries such as steel, cement, ICT, textiles and chemicals. This target became binding with the introduction of the European Climate Law, which entered into force on 29 July 2021 (European Commission, 2023a). As a mid-transition target, by 2030 net greenhouse gas emissions need to be reduced by at least 55% compared to 1990 levels; additionally, and a renewable energy target needs to be reached that requires a minimum of 42.5% renewables in the system. An overview of the EU mid-transition targets is given in Table 2.1. Further targets for the coming years are yet to be specified. The final pillars of the complete package of legislation, the so-called ‘Fit for 55’ package, was adopted on 9 October 2023 and is now set be implemented by the EU Member States.

Table 2.1: Overview of EU Mid-Transition Targets

Target	%	Year
Reduction of EU net greenhouse gas emissions	55% (expected 57%)	2030
Renewable energy (of total energy mix)	Minimum of 42.5%; aiming at 45%	2030
Improve energy efficiency	By 11.7%	2030
All new cars and vans registered in Europe	Zero emissions	2035

RePowerEU - Renewables are at the forefront of Europe’s response to the energy crisis

While the EU is planning to become climate neutral by 2050, which implies that the energy system has to largely decouple from fossil fuels, Europe is currently still very dependent on natural gas, oil, and coal imports. With supply shortages and highly volatile energy prices in the aftermath of the COVID-19 pandemic and the Russian invasion of Ukraine, energy security has become increasingly important for the EU.

For many years the dependency on Russian natural gas was particularly high, covering between 40% and 50% of the EU natural gas demand between 2019 and February 2022. After the geopolitical conflict between Russia and Ukraine started on 24 February 2022, the share of Russian natural gas was gradually, but significantly, reduced to 13% in November 2022. In response to the crisis, a clear signal was sent not only to become less dependent on Russian fossil fuels, but also to achieve faster acceleration to renewable energy. In addition, cooperation and solidarity between member states has become more important.

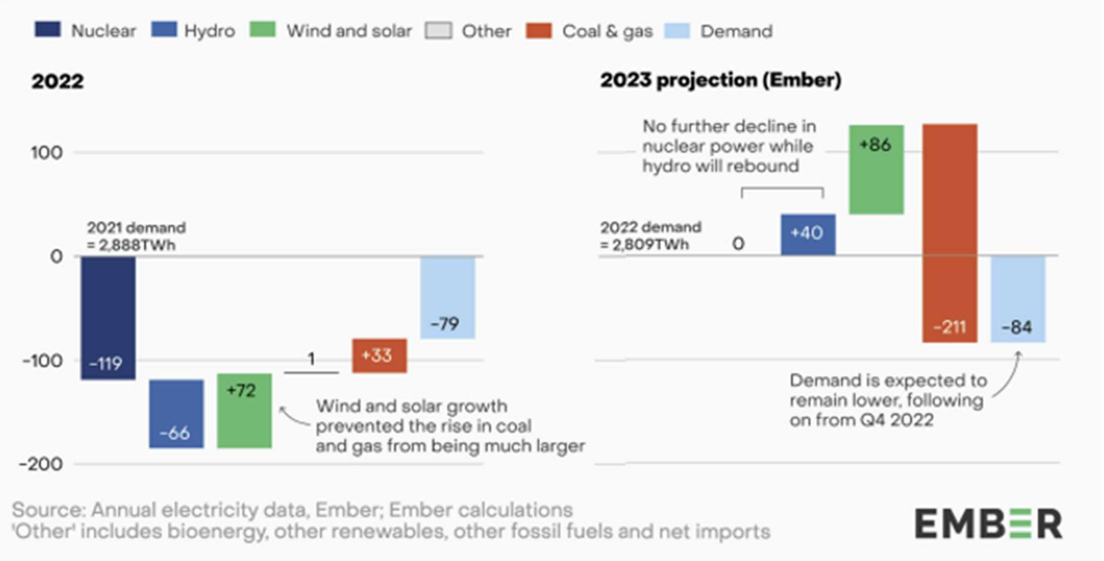
Instead of playing the goals of climate neutrality and energy security against each other, it was politically agreed that the crisis could only be resolved if the EU increased the share of renewable energies in its energy system and accelerated the energy transition. In May 2022, the European Commission proposed 'RePowerEU' as a strategy to reduce the EU's dependency on Russian fossil fuels. The three key components of the strategy are i) an increased expansion of renewable energy, ii) the improvement of energy efficiency and iii) supplier diversification (European Commission, 2022).

Russian natural gas supplies were supplanted by multiple other sources of natural gas: increased liquefied natural gas (LNG imports from mainly the US, Qatar and Nigeria; increased gas imports from Norway, UK and Algeria; and natural gas demand reductions linked with high prices.

Figure 2.6 shows the year-on-year change in electricity generation from 2021-22 (left) and the projection for 2022-23 (right). Nuclear generation was low in 2022 due to outage of French nuclear power plants. Also, hydro power generation was in deficit (66 TWh) in 2022 due to lower rainfall. A rise in wind and solar generation prevented coal and gas use from becoming much larger.

From 2022-23 (right side of the figure) nuclear is expected to hold steady, alongside a rebound in hydro plus 86 TWh of wind and solar. Coal and natural gas-based electricity generation is presumed to be 211 TWh less and total demand is set to be about 84 TWh less than in 2022 due to higher prices and higher energy efficiency.

Figure 2.6: Year on year change in electricity generation (TWh), EU27



Source: Jones et al. (2023).

Clean energy investments – such as renewables, power grids, and energy efficiency – have been augmented by enhanced policy support such as the EU's Fit for 55 package and the REPowerEU plan[3]. They have also been reinforced by a strong alignment of climate

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[3] The European Commission has adopted a set of proposals (Green Deal) to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.

and energy security goals and a focus on industrial strategy as countries seek to strengthen their footholds in the emerging clean energy economy.

Public and private sector investment will be a crucial component to achieve net-zero targets in Europe. Finance programs from development banks such as the European Investment Bank will be crucial to scale up private sector capital. In addition, price stability and inflation expectations are key prerequisites to encourage sustainable investment (IEA et al., 2023).

The crisis triggered by Russia's assault on Ukraine in 2022 has accelerated renewable energy deployment in the EU, driving the bloc to urgently reduce its dependence on Russian natural gas imports. Policy actions in many European countries have led to forecasts up to 40% higher for renewable capacity additions in the EU in 2023 and 2024 compared with pre-2022. Rapid growth in distributed solar PV is the main reason for the more positive outlook, accounting for almost three-quarters of the EU forecast revisions. This is driven by high electricity prices that make solar PV more financially attractive and by additional policy support in key EU markets, especially in Germany, Italy and the Netherlands (IEA, 2023a).

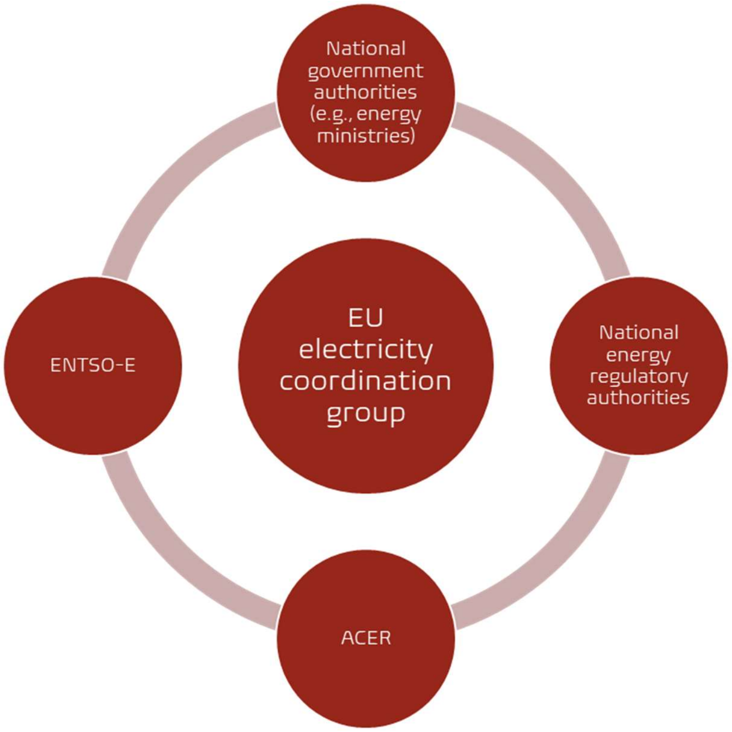
The long-term strategy is for the EU to achieve a fully decarbonised energy system by 2050. The target is to be achieved by phasing out fossil fuels and building out renewable generation. Many studies point to a high share of VRE and electrification of energy-consuming sectors as crucial to decarbonisation, with P2X and carbon capture, utilisation and storage (CCUS) seen as key technologies for hard-to-abate sectors (steel, cement, heavy traffic, etc.).

Cooperation between EU Member States

A common theme in the energy security discussions in the EU is the need for cooperation and solidarity between Member States and other regional partners. Cross-border cooperation, interconnections and a functioning electricity market ensure that electricity can flow between Member States and partner countries and that the different countries can rely on each other. The concept of cooperation to increase the security of supply is also reflected in the EU Energy Platform, which was implemented in April 2022 to aggregate demand and jointly purchase natural gas and (in the future) hydrogen.

Security of supply issues on electricity are monitored and discussed in the Electricity Coordination Group (see Figure 2.7), which consists of national government authorities (i.e., energy ministries), national energy regulatory authorities for energy, the Agency for the Cooperation of Energy Regulators (ACER), as well as the European Network of Transmission System Operators for Electricity (ENTSO-E). As part of the *Clean Energy for All Europeans Package* in 2019, the *Regulation (EU/2019/941)* on risk preparedness in the electricity sector was passed in 2019 (European Commission, 2019). It requires all EU Member States to assess and identify all possible electricity crisis scenarios and develop risk preparedness plans. In the Electricity Coordination Group, best practices and expertise on security of supply in the electricity sector are shared, including risk-preparedness, generation adequacy and cross-border grid stability. Furthermore, the group supports the European Commission in designing new energy security policies.

Figure 2.7: Members of the EU Electricity Coordination Group



Critical infrastructure and cybersecurity

As connections proliferate between traditional energy infrastructure and digital technologies and networks, the European Commission recognises that cyberattacks and cybersecurity incidents pose a risk for the energy sector. Given the interconnections between the electricity grids of the different Member States, an outage in one country might lead to a blackout in another country. In cooperation with ACER, the European Commission has developed a network code on cybersecurity (ACER, 2022c; European Commission, 2020), which will become binding once it is adopted by the Member States.

2.8 Key messages

***Key-messages from the discussion in this chapter are as follows*:**

- **In the coming decades, our energy systems will be in transition. This transitional stage (mid-transition), with a growing share of variable renewable energy (VRE) resources and technological uncertainties, brings about new risks and the need for a redefinition of the concept of *energy security*.**
- **We need a detailed understanding of the specific risks surrounding the ongoing transition, including quantitative metrics to assess these risks and measures to mitigate them.**
- **The coexistence of the fossil-fuel dominated system of the present and the emerging carbon-neutral system of the future creates tensions between two differing operational paradigms.**
- **In many ways China and the EU have the same kind of challenges to reach their zero-carbon targets. These include the technical solutions of large-scale deployment of renewables and CCUS and P2X technologies. However, the history, the decision processes and the political and regulatory framework of the two regions are different.**

3. Energy security risks during transition

This chapter provides a description of energy security risks during transition. An overview of risks is presented in Table 3.1 below. Subchapters 3.1-3.12 describe risks in detail. For a subset of risks that are particularly relevant for both China and the EU, a more detailed assessment is carried out including proposed metrics and suggested mitigation measures.

The energy security risks during and post energy transition can be outlined as indicated in Table 3.1 (not exhaustive). It is important to note that the security risks of a clean energy transition are limited in comparison to the risks of not making that transition. The latter will entail more severe droughts, flooding and heatwaves threatening food and water availability and adding to regional conflict and migration.

The risk evaluations in this chapter focus on three stages of the energy system transition: the current status, mid-transition, and full transition. Regarding the mid-transition, the coexistence of the fossil fuel-dominated system of the present and the emerging carbon-neutral system of the future creates tensions between two rather differing operational paradigms which – among other things – impact infrastructure requirements.

Further, the mid-transition is characterised by an increasing risk arising from overlooking synergies and uncoordinated decision making, making trade-offs more evident and more pressing. The transition towards a zero-carbon energy system is assessed as taking place along two distinct pathways: a pathway based predominantly on CCUS and a pathway based mainly on large-scale deployment of renewables.

Table 3.1: Overview of Energy Security Risks of a System in Transition

	Risk	Description
1	Risk of dependence on imported fuels	Countries heavily reliant on imported oil and gas face potential supply crises and high energy costs if global investment in the sector falls without a corresponding drop in demand.
2	Electricity system risks - key due to electrification of society	Challenges include ensuring a stable supply of critical materials for technologies like wind and solar, as well as addressing flexibility needs for balancing power systems and security of supply risk (can VRE adequately contribute to adequacy and system security?). The risk of insufficient transmission capacity is also an issue.
3	Transition risks	Balancing the reduction of fossil fuel generation with the increase in VRE requires judicious market regulations and mechanisms.
4	Cost of capital risk	The transition demands significant upfront investments, presumably not only in Europe or China but also in India, Indonesia, Brazil, Mexico, South Africa, etc.
5	Geopolitical risks and trade conflicts	Dependence on a small number of countries for critical minerals and challenges in diversifying supply chains may lead to geopolitical tensions and trade conflicts.
6	Cyber-attacks/IT risks	The digitalisation and connectivity of the smart grid increase vulnerability to cyberattacks.
7	Heightened tensions between wealthy and poorer countries	The transition may strain relationships if promised climate assistance is not provided.
8	Technology risk	The implementation of certain technologies, such as CCUS and P2X, are necessary but so far unproven on a large scale. The technology risk could lead to adverse effects, such as extension of fossil fuel dependency, higher energy consumption or less efficiency.

Table 3.1: Overview of Energy Security Risks of a System in Transition		
	Risk	**Description**
9	Climate change impact risk	Renewable generation technologies are influenced by changes in climate conditions, and other generation technologies may be affected by factors like water availability and temperature.
10	Dependence on large-scale VRE and weather patterns (WP2 of this ECECP project – see Chapter 4)	Relying more on VRE poses security risks, especially with reference to unpredictable climate and weather patterns[4].

3.1 Risk of dependence on imported fuels[5]

The risk of dependence on imported fuels in the context of energy security refers to the vulnerability of a country's energy supply in the case of a heavy reliance on external sources for essential fuels like oil, natural gas, or coal. This dependency can expose a nation to potential supply disruptions, price volatility, geopolitical tensions, and economic instability if there are interruptions in the global supply chain or conflicts with key fuel-exporting countries.

Risk of dependence on imported fuels in China

China holds a prominent position in the global commodity and fuels market, and its major footprint becomes clear from a simple inspection of the data shown in **Table** 3.2. China is the world's largest net importer of crude oil, sourced mainly from Saudi Arabia and Russia, and it is also the largest net importer of natural gas. Furthermore, China is the world's largest producer of coal, although it imports significant additional amounts from sources like Indonesia, Russia, Australia, the US and Colombia (S&P Global, 2023).

Almost two thirds of China's natural gas imports are in the form of LNG with Australia its top supplier, followed by Qatar and Malaysia. The remainder is imported via pipeline from the Commonwealth of Independent States (CIS) and Russia (bp, 2022).

Table 3.2: Selected Indicators on China's Footprint on the Global Fuel and Commodity Market			
Fuel/Technology	**Position**	**Indicator**	**Year**
Crude oil	Largest net importer	505 Mt in 2019	2019
	Sixth largest producer	195 Mt (4,7% of world total)	2020

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[4] The second part of this report (WP2) quantitatively assesses the risks of being dependent on future large scale variable renewables in the power system (2050 and 2060). The report includes a comparative analysis of the power system adequacy contribution (or load carrying capacity) of RE resources deployed in Europe vis-a-vis China.

[5] Note: The focus here is on fossil fuels. The assessment does not include hydrogen and green fuels.

Table 3.2: Selected Indicators on China's Footprint on the Global Fuel and Commodity Market

Fuel/Technology	Position	Indicator	Year
Natural gas	Largest net importer	125 bcm	2020
	Fourth largest producer	191 bcm (4.8% of world total)	2020
Coal	Largest producer	3764 Mt (49.7% of world total)	2020
	Largest net importer	306 Mt	2020

Source: International Energy Agency (IEA, 2021b) Note: 2020 data is provisional.

Nuclear power is also important to China, both now and in the future energy system. As of June 2022, China had the world's third largest fleet of civil nuclear reactors, composed of 54 operable reactors (55.8 GW), just behind the US and France. By comparison, France has 56 operable reactors and a total installed capacity of 61.4 GW.

China's nuclear capacity has been rising in recent years and is expected to continue this trend in the years to come: 40% of all new nuclear capacity currently under construction is in China. Nuclear appears to be an important element of China's energy transformation, as it secures baseload electricity generation, accounts for low CO_2 emissions and offers a means to improve technological independence from foreign sources (Andrews-Speed, 2023).

Historically, China has cooperated with Russia to develop and build nuclear enrichment plants, but most of its recent enrichment capacity is indigenous (World Nuclear Association, 2021), which is in line with the country's overall strategy to indigenise nuclear technology. As Andrews-Speed (2023) notes, Chinese research institutes and companies have the capacity to develop a variety of new, export-quality technologies, such as high temperature gas-cooled, molten salt and fast neutron reactors, as well as floating plants and nuclear fusion, and have already completed additions to the country's nuclear power system.

China still relies on foreign suppliers for all stages of the nuclear fuel cycle, from uranium mining through to fabrication and reprocessing, but most of all for supplies of uranium. However, it is China's goal to diversify this supply by sourcing one-third domestically, an additional one-third through foreign equity in overseas mining ventures (see Table 3.3), and to purchase one-third on the open market (World Nuclear Association, 2021).

Table 3.3: Chinese Equity in Overseas Uranium Mining Ventures

Company	Country	Mine	Equity %	Start of production with Chinese equity
CNUC	Niger	Azelik	37,2% + 24,8% ZXJOY	2010 but now closed
		Imouraren	25+, more pending	On hold
	Namibia	Langer Heinrich	25+, more pending	2014
		Rössing	69	2019
	Kazakhstan	Zhalpak	49	2017
CGN-URC	Namibia	Husab	90	2016
	Kazakhstan	Irkol & Semizbai	49	2008, 2009
	Uzbekistan	Boztau black shales	50	Uncertain

Table 3.3: Chinese Equity in Overseas Uranium Mining Ventures

Company	Country	Mine	Equity %	Start of production with Chinese equity
	Canada	Patterson Lake	20	2023

Source: World Nuclear Association (2021).

Looking forward, the key development to observe is that China's demand for uranium is expected to increase to between 18 500 tonnes (for 100 reactors) and 24 000 tonnes (for 130 reactors) by 2030. In recent years, China has imported from countries like Kazakhstan, Uzbekistan, Canada, Namibia, and Australia (World Nuclear Association, 2021). An adequate uranium import diversification strategy must be part of China's general strategy to mitigate fuel import risk.

Under the policies announced so far, the assessment is that China is not likely to achieve its dual carbon target, and therefore under the status quo there is a very high risk of fossil fuel dependence.

Evaluation, China

If carbon offset technologies such as CCS define China's pathway to carbon neutrality, the risk of dependence on imported fossil fuels is expected to remain, as full independence from fossil fuels is unlikely to be achieved. Instead, carbon offset technologies allow the energy system to continue its reliance on fossil fuels without significantly curbing fossil fuel demand. The risk remains: global fossil fuel markets are likely to continue being volatile in the future due to a variety of factors, such as supply disruptions and geopolitical tensions, as well as the fact that global fossil resources are finite.

As CCS will play an important role under the pathway that employs a high degree of offset technologies, a large amount of captured CO_2 will be available, which can be used to produce a range of synthetic fuels (e.g. e-methanol, synthetic jet fuel) which may help to mitigate the dependence on imported fossil fuels.

In contrast, if China adopts a pathway to carbon neutrality that prioritises the decisive adoption of VRE sources, there will be significant less reliance on fossil fuels. Although volatility in these markets is likely to continue, its impact will be less.[6]

Risks of dependence on imported fuels in the EU

According to Eurostat (2023), all EU Member States have been net importers of energy since 2013. In 2020, the EU imported 57.7% of energy, with some countries such as Sweden (33.5%), Romania (28.2%) and Estonia (10.5%) having relatively low energy

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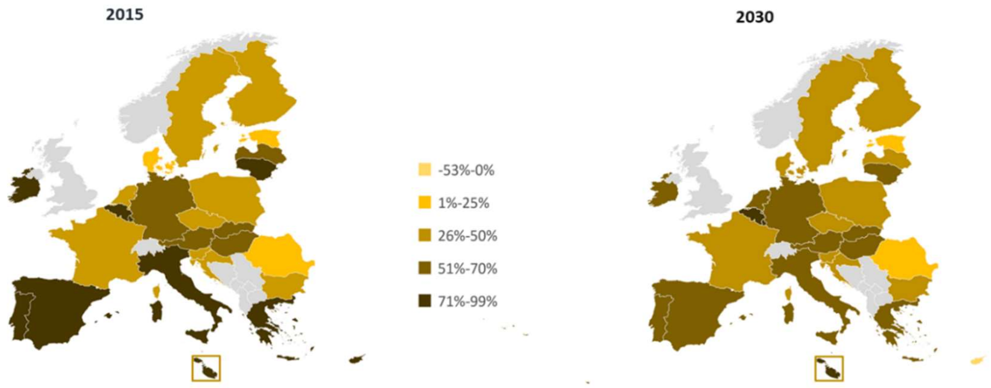
[6] In practical terms China will in the future to some extent be dependent both on deploying VRE and developing CCS.

dependency rates, while other countries such as Malta, Cyprus and Luxembourg are almost entirely dependent on energy imports (see Figure 3.1).

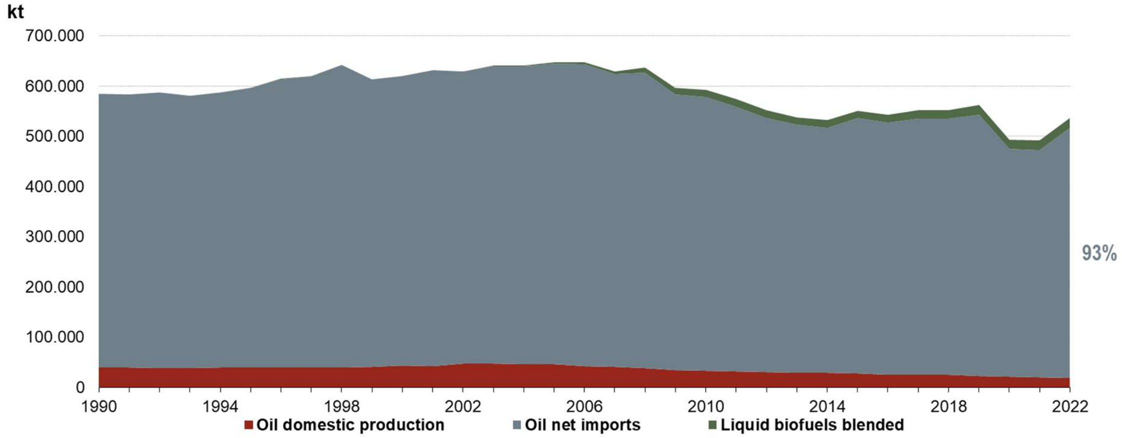
Figure 3.1: Energy import dependence by Member State in 2015 and 2030



Source: European Commission (2021).

Natural gas dependency in 2022 was 89% (see Figure 3.2).

Figure 3.2: Supply of natural gas in the EU electricity grid

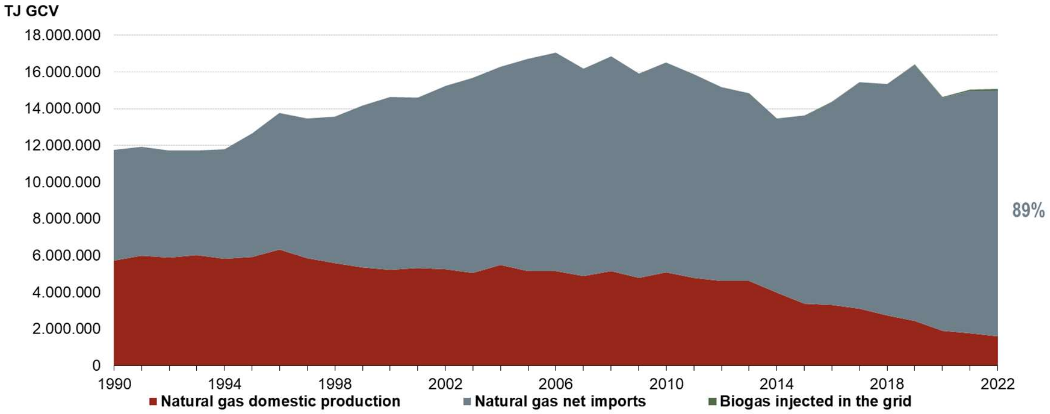


Source: Eurostat (2023).

Europe has been heavily dependent on imports of Russian natural gas, oil, and coal for many years. Russian natural gas covered between 40% and 50% of the EU's natural gas demand between 2019 and February 2022. Following the onset of the geopolitical conflict between Russia and Ukraine on 24 February 2022, the share of Russian natural gas was gradually, but significantly, reduced to 13% in November 2022.

93% of the EU's oil supply is imported (see Figure 3.3).

Figure 3.3: Supply of oil and blended biofuels in the EU



Source: Eurostat (2023).

Evaluation, EU

As a consequence of the geopolitical conflict in Ukraine, the EU has replaced Russian gas with other sources of natural gas:

- Increased LNG imports from mainly US, Qatar and Nigeria.
- Increased gas imports from Norway, UK and Algeria.
- Natural gas demand reductions due to high prices.

As of November 2022, LNG and pipeline gas imports from Norway accounted for roughly 25% each of all EU imports, while Russia accounted for 25% (including LNG). Algeria represents 12% of the supply, and the remaining 13% is a mix of minor imports from other countries.

Europe imports almost of its oil supplies. However, these imports can be traded in the open market and from many different countries and are not assessed as critical. The same applies to European coal consumption. European coal consumption has steadily decreased over the last decades.

Proposed metrics, China and EU

Metrics to quantitatively assess the risks associated with oil and gas imports include:

- Import dependency, i.e., the share of imported fuels (both fossil and synthetic) in the total domestic supply in each scenario.
- Volatility of import prices and supplies.

Mitigation measures, China

To mitigate this risk, China may implement some of the following policies to diversify its supply base:

- Increase cooperation with foreign suppliers, not only to develop and expand infrastructure, but also to develop new trade partnerships. This is closely related to China's Belt and Road initiative, which has shaped the country's foreign policy in the last decade.
- Diversify imports from exporting countries.
- Consolidate supply chains for the development of synthetic fuels.
- Commit to a decarbonisation pathway involving renewables.

Mitigation measures, EU

Mitigation measures may include:

- Continue to diversify imports from exporting countries.

3.2 Electricity system risks - key due to electrification of society

Challenges include ensuring a stable supply of critical materials for technologies like wind and solar, as well as addressing flexibility needs for balancing power and security of supply (SoS) risk.

3.2.1 Electricity system risks - flexibility needs

Flexibility is key to a successful energy transition. The need for flexibility in the energy system encompasses ensuring adequate capacity through demand response, P2X, EVs, dispatchable generation (both in terms of capacity and ramping), and efficient transmission to balance VRE generation across time and space.

Flexibility sources are:

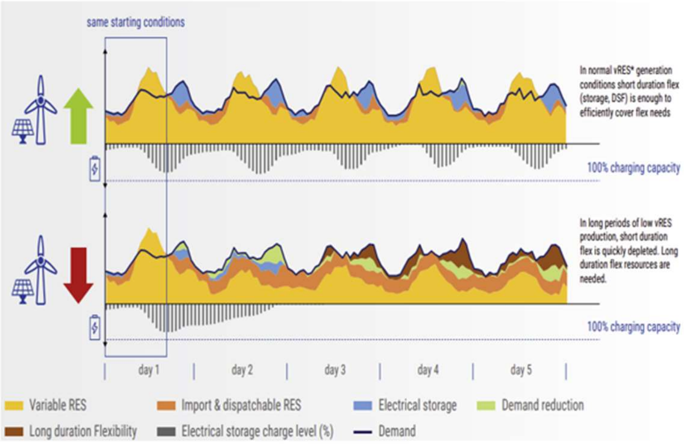
- Flexible demand and demand response.
- P2X.
- Storage: EV and batteries and hydro storage.
- Dispatchable generation based on biomass/biogas, hydrogen and hydropower.
- Transmission with import/export options.

From a system point of view, two main types of flexibility needs can be identified, each requiring different flexibility resources:

- short duration flexibilities (from milliseconds up to a few hours, to balance the system within the day and ensure system stability).
- long duration flexibilities (up to several weeks, to compensate for long periods with shortage of wind, solar and hydro generation).

The need for both types of flexibility resources is illustrated in Figure 3.4: short-duration flexibility resources can provide significant amounts of power, but do not have enough energy stored to last several days and need to be complemented by high-density energy resources for long-term flexibility provision.

Figure 3.4: Use of short-duration and long-duration flexibility resources



Flexibility sources, e.g.,:

- Short term:
  - Electrical storage (batteries)
  - Demand response
  - Dispatchable Hydro, Bio
  - Import (interconnection)
  - ..
- Long term
  - Dispatchable Hydro, Bio
  - Hydrogen power
  - Interconnection
  - …

Source: ENTSO-E (2022).

3.2.2 Electricity system risks – security of supply risk

The security of supply (SoS) risk revolves around whether VRE can effectively ensure security, encompassing factors such as adequacy, resilience, and inertia. This risk can be further segmented into adequacy of generation and transmission, as well as system security, which encompasses system resilience.

Adequacy risk

Weather parameters dictate whether VRE (wind and solar) can generate energy and therefore the VRE contribution to adequacy is uncertain compared to traditional dispatchable generators (e.g. fossil-fuelled and nuclear generators).

Adequacy from VRE explained

In the EU, the implementation of the Clean Energy Package (2019) brought about a revised resource adequacy assessment framework, which – unlike its predecessor – now explicitly accounts for the variability of weather conditions and its impact on both VRE generation and demand. The revised framework, which has a 10-year horizon, builds on a deterministic forecast of generation (based on scenarios), planned outages, and explicitly adds an uncertainty component into the assessment. To achieve this, a probabilistic assessment of wind, solar and hydro generation patterns, and forced outages of generators and transmission and climate-dependent consumption patterns are incorporated into several alternative scenarios. Rather than producing point estimates of resource adequacy, the framework produces adequacy measures that explicitly account for the inherent uncertainties.

Figure 3.5 offers a graphical presentation of the methodological approach. Forced generation and transmission outages are assessed probabilistically. Variable generation of wind, solar and hydro are described via time series for several years. Specifically, 34 different climate years are represented (that is to say, 34 different climate scenarios). On the demand side, DSR (demand side response) and temperature-driven demand are also considered (see Figure 3.6).

Figure 3.5: Method of adequacy assessment

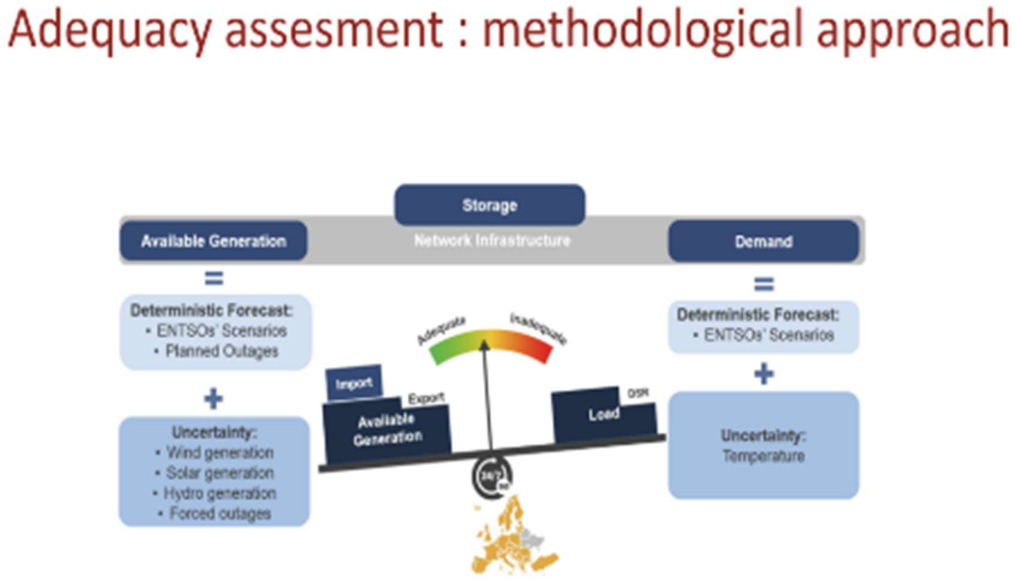
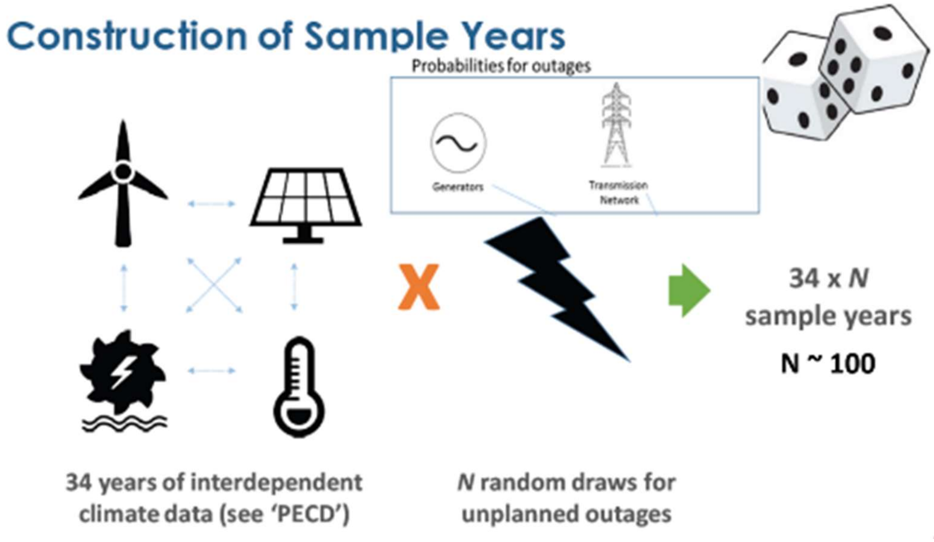


Figure 3.6: Construction of sample years

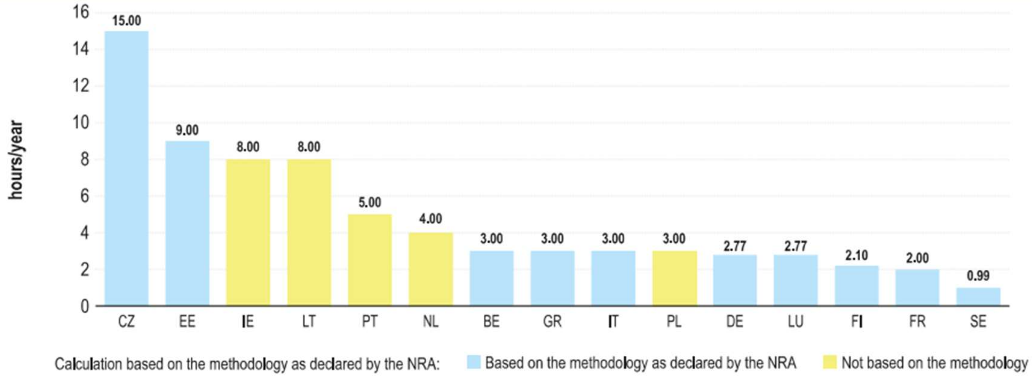


For each of the 34 meteorological years, a number N of sample years (each of 8 760 hours) are constructed using a Monte Carlo simulation approach. For example, if N=100, then 3 400 possible realisations are calculated. As the number of realisations increases, the uncertain statistical parameters LOLE (loss of load expectancy) and EENS (expected energy not served) stabilise.

In China, deterministic methods are employed to assess power adequacy, taking into account demand forecasts, including peak and off-peak periods.

Figure 3.7 shows the LOLE (hours per year) for a number of countries in the EU (ACER, 2023).

Figure 3.7: LOLE (hours per year) for a number of countries in the EU



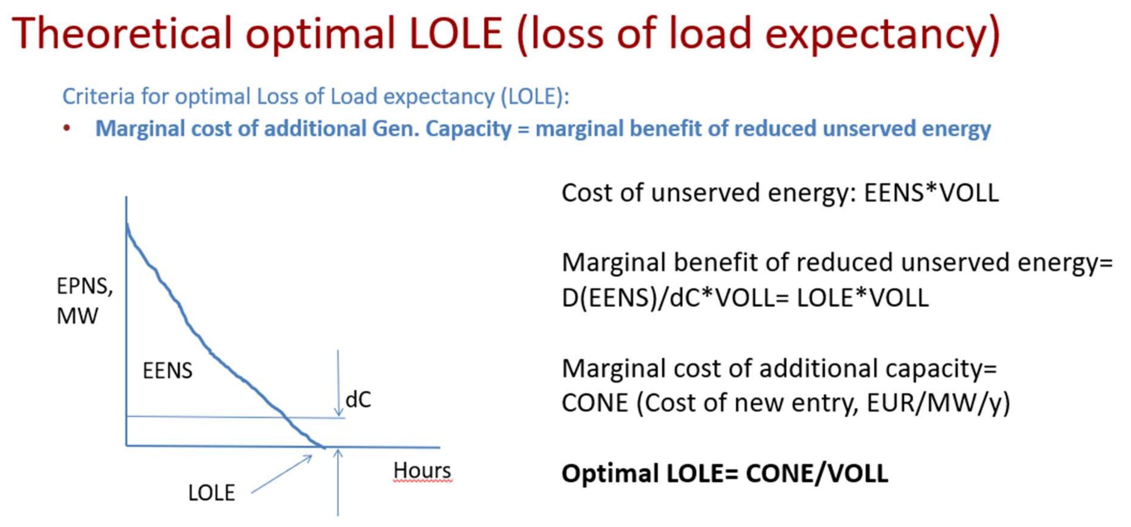
Source: ACER based on NRA data.

Source: ACER (2022b).

Figure 3.8 presents the derivation of a simple formula for the optimal level of LOLE. As can be seen, EENS decreases as installed capacity increases. EPNS is the expected power not served. Increasing capacity (dC in the Figure) is only optimal when the marginal benefit of adding capacity equals the marginal cost of adding capacity. Note here that the Value of Lost Load (VOLL) is the unit cost of not serving load, and CONE is the Cost of New Entry. The optimal LOLE is equal to CONE divided by VOLL.

Figure 3.8 shows optimal LOLE (loss of load expectancy).

Figure 3.8: Optimal LOLE (loss of load expectancy)



Theoretical optimal LOLE (loss of load expectancy)

Criteria for optimal Loss of Load expectancy (LOLE):

- **Marginal cost of additional Gen. Capacity = marginal benefit of reduced unserved energy**

Cost of unserved energy: EENS*VOLL

Marginal benefit of reduced unserved energy= D(EENS)/dC*VOLL= LOLE*VOLL

Marginal cost of additional capacity= CONE (Cost of new entry, EUR/MW/y)

Optimal LOLE= CONE/VOLL

System security risk

As generation technologies based on solar and wind are replacing traditional thermal power plants, more and more inverter-based generation (i.e., asynchronous connection) is connected to the electricity system. These new inverter-based technologies have different electrical engineering characteristics compared to traditional central power plants. One important aspect is that the system inertia will decrease with increasing amounts of inverter-connected VRE. Lower inertia means higher frequency deviations during system faults and therefore lower resilience and lower security of supply. One remedial measure is to introduce very fast system response mechanisms from rapid frequency reserves.

Increasing levels of variable inverter-based renewable energy sources are prompting questions about how the systems would operate when the system approaches 100 % VRE. These kinds of issues are currently heavily researched around the world.

3.2.3 Electricity system risks - adequate transmission risk

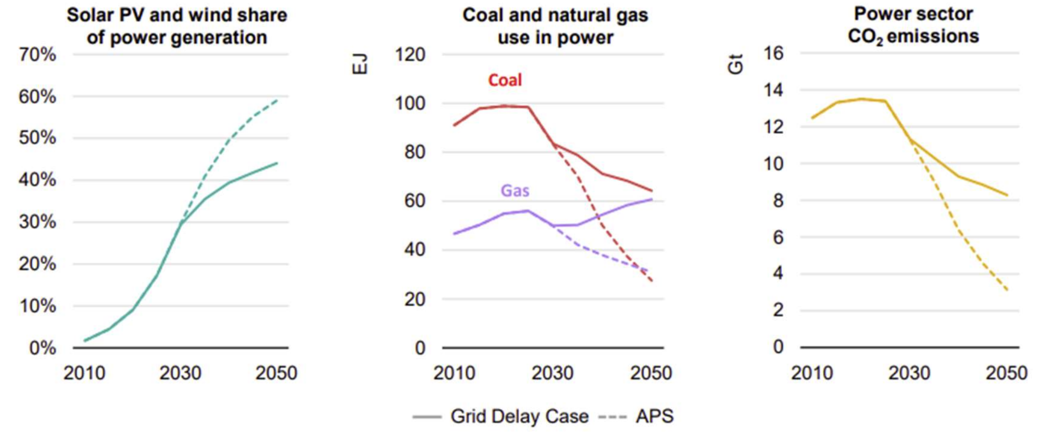
Adequate transmission capacity is an important component of energy and system security. Additionally, transmission is a key measure of flexibility for balancing the power system and securing energy delivery from areas with a surplus to those with a deficit or with more expensive supply. With the growing development of VRE (solar and wind) in the power system and the often uneven geographical and timely distribution of VRE resources across regions, the value and necessity of transmission grow.

The IEA as illustrated the importance of transmission grids in the transition. It did this by comparing the countries' APS (Announced Pledges Scenario) 2020-50 with a scenario with delayed grid development. The delay corresponds to 15%-20% less PV and wind being able to connect to the grid by 2050. This will lead to higher generation based on fossil fuels and therefore higher CO_2 emissions (IEA, 2023d). The result is shown in Figure 3.9.

It follows that replacement of coal and natural gas in the power sector will be slower and the CO_2 emissions will decrease significantly less if grid development is delayed.

Figure 3.9: Worldwide consequences of delayed grid development (power sector)

Share of solar PV and wind, coal and natural gas use in power generation, and power sector CO_2 emissions worldwide in the Grid Delay Case and the Announced Pledges Scenario, 2010-2050



IEA. CC BY 4.0.

Notes: EJ = exajoules; Gt = gigatonnes.
Sources: IEA analysis based on IEA (2022), World Energy Outlook 2022.

Source: IEA (2023e).

Outline: Transmission infrastructure planning

Europe's ENTSO-E methodology uses a coordinated and comprehensive transmission grid planning approach, which includes development of scenarios, screening of potential new transmission assets, and CBA (cost benefit analyses). The aim is to ensure system reliability, guarantee power supply and integrate more renewable energy (RE) at the lowest possible cost.

The ECECP 2021 project 'A4.1.1: ENTSO-E Grid Planning Modelling Showcase for China' showed that a Chinese market-based approach, where transmission expansion is market led, could achieve significant CO_2 emission reductions in China's power system. The reductions can be achieved because transmission expansion will allow higher amounts of renewables to be generated and transported to consumers, thereby displacing coal-fired power generation. So, besides energy security, increased transmission capacity brings economic trading benefits, CO_2-reductions and reduced curtailment of VRE.

It is beneficial to use an integrated approach for infrastructure planning. A key challenge for the power system is how to integrate high VRE and ensure system adequacy with very low fossil-based generation. In addition, the power sector has increasingly stronger links with the consumption side, including CCUS and P2X. So, there is a need to optimise power, natural gas, green gas and liquid fuel infrastructure and thereby ensure a successful sector-coupling and optimal coordination among energy carriers. This issue is investigated in the ECECP project B2.6 *Investment and Technologies for Net-Zero Carbon Infrastructure*, which will be finalised in Q4, 2023.

3.2.4 Insufficient transmission system integration

Insufficient transmission system integration refers to the vulnerability and potential disruptions in the energy supply that can occur due to inadequate integrated infrastructure for transmitting electricity. This can lead to inefficiencies, congestion, and limitations in the flow of energy from generation sources to consumption centres, especially in regions heavily reliant on VRE.

Insufficient transmission system integration in China

Example: Guangdong and Fujan

Insufficient transmission system integration in China, exemplified by Guangdong and Fujian, led to challenges in meeting rising electricity demands and harnessing renewable energy potential. Today, however, a grid connection approved in 2020 is now mutually benefiting both provinces and enhancing flexibility in accommodating clean energy sources.

Guangdong and Fujian are two major coastal provinces in China. Electricity consumption in Guangdong is 790 TWh and is 1.7 times more than that in Fujian in 2022. Both provinces are undergoing rapid development. It is estimated that in 2025, the maximal power load will be more than 55 GW in Fujian and 155 GW in Guangdong. Compared to 2020 levels, this represents a growth of 30% and 22% in Fujian and Guangdong respectively.

From the energy supply side, Fujian has a greener energy structure than Guangdong. Non-fossil fuel generation accounts for around 48% of total power generation in Fujian, while the VRE share in Guangdong was just above 30% in 2022.

Hydro power in Fujian and hydro power transmitted from Yunnan to Guangdong are associated with different watersheds, with distinct inflow characteristics. In addition, the summer comes later in Fujian than in Guangdong. Therefore, Fujian and Guangdong could see clear benefits from being connected.

However, these two provinces are located within separate power system regions, creating technical difficulties when contemplating grid connections. In addition, as the connection would not always be at capacity, in contrast to the connection from Yunnan to Guangdong, it might result in higher transmission costs for the two provinces.

However, as demand for clean energy rose and the need of flexibility in the system operation increased, the connection was finally approved by NDRC in 2020 and was put into operation in 2022. According to Fujian Daily, the connection started to provide mutual benefits to both provinces in the summer of 2023.

According to the agreement between the two provinces, Fujian provides electricity to Guangdong from March to June and from October to November, while Guangdong provides electricity to Fujian in July, August, September and December, thus resolving the tensions between local production and demand. The connection also provides the flexibility to accommodate a higher share of wind and solar power in the system by integrating the interprovincial spot market.

Example: Yunnan and Sichuan

A similar situation applies to Yunnan and Sichuan. Insufficient transmission system integration between Yunnan and Sichuan, despite their proximity, has hindered their ability to share and balance their renewable energy resources efficiently, resulting in power shortages exacerbated by factors like weather variations and increased demand from industries due to their fluctuating green energy supplies.

Even though Yunnan and Sichuan are on the left and right bank of the Jinsha River, the weather conditions vary. The temperature in Yunnan goes up in spring, while it does not get particularly hot in Sichuan until late June. The temperature can remain very high in Sichuan until October, but stays more moderate in Yunnan during the summer.

Abundant green energy resources in both provinces usually yield significant aluminium electrolysis and PV production. Power shortages started to occur in 2019 and intensified during a long-lasting drought in the Yangtze River watershed in 2022. Transmission integration of the two provinces could provide flexibility support by making full use of the differences in electricity demand. Additional transmission integration could have mitigated the power shortages.

General note on transmission system integration in China

The challenge of transmission system integration in China extends beyond physical capacity and is influenced by factors like market-led expansion, climate policies, and the dominant energy transition pathway, with the adoption of renewable energy technologies playing a crucial role in motivating integration to achieve a net-zero energy system.

In general, the issue goes beyond physical capacity and is affected by the way in which the transmission system is currently employed and integrated. The preference for long-term contracts, and for locally-generated electricity output, has an impact on the pricing of transmission capacity utilisation in China.

The ECECP 2021 project ‘A4.1.1: ENTSO-E Grid Planning Modelling Showcase for China’ showed that a Chinese market-based approach, where transmission expansion is market led, could achieve significant improvements. Besides energy security benefits, transmission integration brings with it CO_2-reductions and reduced curtailment of VRE.

Currently, an insufficiently integrated Chinese system presents significant risks, and the absence of more ambitious climate policies mean there is little motivation for integration of the Chinese system.

To achieve a net-zero energy system, it is essential to rely on a high share of VRE, complemented by CCS technology that can address hard-to-abate emissions. If carbon offset technologies dominate the transition and therefore lower the need for grid integration, the motivation for transmission expansion may be relatively limited. This may lead to a relatively high risk of insufficient transmission system integration. In contrast, if the transition is mainly based on renewables, the risk of insufficient transmission is lower because it is assumed that the decisive adoption of renewable energy technologies will be a motivating factor for integration of the Chinese transmission system.

Proposed metrics, China

To assess the presence of this risk, the following metrics can be considered:

- Frequency of inter-provincial trades.
- Liquidity of the national market.
- Physical inter-provincial transmission capacity.

Mitigation measures, China

To mitigate this risk, some of the following measures can be implemented:

- Integrating the transmission system into the market mechanism, for example through implicit capacity auctions in the market coupling mechanism.
- Integrated generation-transmission planning.
- Adopting socialised cost recovery mechanisms.
- More flexible inter-provincial transmission, which can adapt to the seasonal characteristics of resources in different regions.
- Accelerating the development of energy storage.
- Expanding cross-regional infrastructure to transmit renewable power, pursuing transmission rescheduling, netting supply-demand imbalances and expanding resource-sharing areas.

Insufficient transmission system integration in the EU

The Fit for 55 Package and REPowerEU Plan are set to fast-forward the energy transition to net zero by 2050. Key to this will be the rapid replacement of fossil-fuel generation by renewable energy sources, more electrification of other sectors, energy efficiency, and interlinking the various energy sectors.

According to ENTSO-E's latest transmission system studies (2022), the transmission system needs to permeate all of Europe, with an additional 64 GW required at around 60 borders in 2030 compared to capacities in 2025. By 2040, 24 GW of additional cross-border capacity is required, on top of the increases identified for 2030. Additionally, 41 GW of storage and 3 GW of CO_2-free peaking units would be needed to support Europe's move towards a carbon-free power system and ensure continuous and cost-effective access to electricity (ENTSO-E, 2022b).

ENTSO-E's Ten-Year Network Development Plan (TYNDP) for Europe in 2022 further finds that when system needs are taken into account, it allows a more efficient use of the pan-European generation mix, translating into savings of EUR 9 billion/yr between 2025 and 2040, with a direct impact on consumers' electricity bills. The curtailment of renewable energy is significantly reduced, by 42 TWh/year in 2040 and replaces more expensive and carbon-intensive thermal generation. A more efficient use of the European generation mix translates into significant CO_2 emissions reductions of 31 Mt/yr in 2040, helping Europe to achieve its Green Deal objectives (ENTSO-E, 2023c).

From the ENTSO-E studies it follows that the European transmission infrastructure is of paramount importance for the energy system transition. It also follows that transmission needs will increase in line with the amount of renewable energy capacity installed. Wind power installed on favourable wind sites in Northern Europe (e.g. offshore wind in the North Sea) will need to be transported to load centres in central Europe. In the same way, PV installations in southern Europe will need transmission capacity for transport of energy to other distant areas.

There is also a challenge for the EU's distribution grids. According to REPowerEU, Europe will see an additional 50 to 60 million heat pumps, 65 to 70 million electric vehicles (EVs) and over 600 GW of additional renewable capacity. Around 70% of that capacity will be directly connected to distribution grids. Even as they become ever more critical to the continent's decarbonisation, Europe's distribution grids face the challenges of scarce capacity, cumbersome permitting processes, and insufficient investments (Eurelectric, 2023).

Therefore, Europe’s ageing distribution grids need a multi-billion euro step change in investment. At the same time, existing grids should be better optimised and digitalised and made smarter and more flexible to manage and spread loads, thus maximising efficiency. Meanwhile, better information makes for better decisions and planning, so data-sharing between system operators, market players and national authorities is paramount (Eurelectric, 2023).

Proposed metrics, EU

To assess the presence of this risk, the following metrics can be considered:

- Price differences across boundaries of price areas in the European wholesale market.
- Physical inter-provincial transmission capacity.
- Frequency of congestion on interconnectors.
- Liquidity of the national market.

Mitigation measures, EU

To mitigate this risk, some of the following measures can be implemented:

- Build new infrastructure/expand existing transmission where profitable (benefits>costs).
- Adopt socialised cost recovery mechanisms in countries where this is not currently applied.
- Adopt CBCA (cross border cost allocation) as a method to enable cost sharing.
- Make better use of existing capacity (e.g. dynamic line rating)
- Integrated generation-transmission planning.
- Accelerate the development of energy storage.

3.2.5 Electricity system risks - inflexible and inefficient energy demand

Energy efficiency is a cost-effective strategy to enhance near- and long-term energy security at local, national and regional levels. A multitude of energy efficiency solutions for buildings, vehicles, appliances and industrial processes are available today. Smart grids, digitalisation and related innovations are powerful tools to enhance system-wide energy efficiency and flexible energy demand.

Inflexible and inefficient energy demand in China

One important source of energy security risk in China's energy transition is the absence of a flexible and efficient energy demand responding to energy price signals[7]. This in essence means that demand does not respond via market signals to the relative scarcity of an energy resource, and it does not create opportunities for alternative technologies to deliver the same energy service with lower energy input.

While the discussion on the absence of flexibility has been broadly debated in the context of the power sector, closely related ideas apply to other areas, such as demand for fossil fuelled transportation or heat demand during the winter months.

Digitalisation and smart metering are among the main technological barriers preventing demand-side flexibility in the power sector, but the same can be said of heat demand, or any other commodity whose consumption is difficult to observe directly and measure. The removal of these technological barriers is only a pre-condition for demand to be flexible. A root cause for the absence of flexibility is that price controls dampen the signal reflecting relative scarcity and consumers have no incentive to adjust their energy use.

In the context of China's energy transformation, in which market-oriented reform is embraced as a guiding principle, the decision to allow parts of the system to operate under market conditions while others remain directly controlled raises the risk of inflexibility and inefficiency. More specifically, it is particularly risky to prevent input prices from feeding through to retail prices, as this could trigger events that could compromise energy security.

An example of this absence of a pass-through mechanism was the 2021 power crisis when market coal prices increased and yet final electricity customers paid fixed tariffs. Not only did this place coal generators under financial pressure, as they could not recover costs from end users, but the latter were unable to see the price signals that reflected the actual cost of producing electricity.

Under stated policies, there is a substantial risk that inflexible and inefficient demand will persist, without a higher ambition for carbon neutrality. Similarly, the mid-transition may also present these issues as, although market-oriented reforms are under way, a full adoption of market mechanisms is not yet complete, which means costs are not adequately reflected or fed through in the entire energy system.

If large-scale deployment of renewables forms the bedrock of decarbonisation, it is more likely that incentives for flexibility and efficiency will be present than if carbon offsetting technologies define China's energy transformation.

Risk evaluation, China

In the future mid-transition, there is a high risk of inflexible and inefficient demand. Here, it is assumed that market-oriented reforms are underway, but that a full adoption of market mechanisms is not yet complete, meaning that costs are not adequately reflected or fed through in the entire energy system.

At the full transition stage, this risk depends on the pathway adopted towards net zero. If the transition involves high deployment of carbon offset technologies, the risk is assessed

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[7] China has a long history on Demand Side Management, especially when the energy supply is inadequate as e.g. in the 1990s. The grid company or the local government has the right to decide who must reduce their energy needs at a particular time, and it draws up a priority list of users.

to be higher than in the renewable-based pathway with accelerated deployment of renewables. The main reason for this difference is that in the first case, technological choices do not embrace flexibility and focus on a high level of electrification while in the latter case, a variety of flexibility-enabling technologies is present.

Proposed metrics, China

To assess the presence of this risk, the following metrics can be considered:

- The degree of cost reflectiveness in different end-use energy prices at different levels of time resolution (hourly, weekly, monthly, yearly) and in different consumer groups (industrial, commercial, residential).
- The short-term fluctuation of retail energy prices in response to variations in input prices.
- The coverage and degree of adoption of smart metering technology.
- The potential for retrofitting as well as technology and fuel substitution measures.

Mitigation measures, China

To mitigate this risk, the following measures can be implemented:

- Ensure all energy prices reflect costs while offering energy consumers protection in the case of sudden price volatility.
- Adopt a decisive initiative to measure and digitise energy consumption while creating measures to incentivise consumer awareness.
- Create incentive mechanisms for retrofitting and technology substitution.

Inflexible and inefficient energy demand in the EU

Energy efficiency is one of the key pillars not only of EU's climate objectives but also of plans to reduce dependence on fossil fuels from abroad and to increase security of supply and the use of renewable energy. However, it is often underestimated in existing planning and investment programs in the EU and beyond. To tackle this issue, the EU Commission responded by proposing a clearer priority for the ‘energy efficiency first principle’ in the recast Energy Efficiency Directive, adopted in July 2021, accompanied by a formal recommendation to EU Member States and detailed guidelines on its application, adopted in September 2021 (European Commission, 2023b).

Demand Side Flexibility (DSF) is the capacity to change end-user energy usage from their normal or current consumption patterns in response to changes in the price of energy over time, or to incentive payments. These price changes or incentives are normally market-related but in the case of electricity could also be related to, for example, grid congestion.

In Europe, markets have been implemented in the energy sector over the past two to three decades. More recently national plans for the roll out of smart meters to end-consumers have been implemented. These meters are already offering many end-users of electricity to react to energy prices and consume less when prices are high. This development has allowed the pass-through mechanism for prices from generation to end-users to make more progress compared to China.

Risk evaluation, EU

In the future mid-transition, there is a moderate risk of inflexible and inefficient demand in some countries. Markets are fully operational in many Member States, while in others market-oriented reforms are still to be implemented, particularly in the end-user segment where a lack of smart meters and digitalisation presents barriers to demand flexibility.

At the full transition this risk depends on the pathway towards net zero. If the transition involves high deployment of carbon offset technologies, the risk is assessed to be higher than in the renewable-based pathway with accelerated deployment of renewables. The main reason for this difference is that in the first case, technological choices do not embrace flexibility and do not focus on high levels of electrification while in the latter case, a variety of flexibility enabling technologies are present.

The proposed metrics and mitigation measures are very similar to those in China.

Proposed metrics, EU

To assess the presence of this risk, the following metrics can be considered:

- The degree to which different end use energy prices reflect costs at different levels of time resolution (hourly, weekly, monthly, yearly) and consumer groups (industrial, commercial, residential). This will vary from country to country.
- The short-term fluctuation of retail energy prices in response to variations in input prices in the different EU Member States.
- The coverage and degree of adoption of smart metering technology in the different EU Member States.
- The potential for retrofitting and for technology and fuel substitution measures in the different EU Member States.

Mitigation measures, EU

To mitigate this risk, the following measures could be implemented. Implementation varies dependent on the progress already achieved in the specific country:

- Further action to ensure all energy prices reflect cost, while ensuring that energy consumers are protected through alternative measures in the case of sudden price volatility.
- Adopt decisive steps to measure and digitise energy consumption while creating measures to incentivise consumer awareness.
- Create incentive mechanisms for retrofitting and technology substitution.

3.3 Transition risks

Balancing the reduction of fossil fuel generation with the increase in VRE requires meticulous market regulations and mechanisms.

Uncoordinated technology transition in China and the EU

Seen from a system-wide and long-term perspective, it is a complex task to identify when the transition to a new technological and operational paradigm is complete. Energy planners and policymakers are required to perform the difficult task of 'phasing in' new technologies and 'phasing out' traditional ones. However, the pace at which this phase-in/phase-out process takes place is inherently risky: there are no objective means to determine when the transition is complete, nor the optimum time to shift from one technology to another. Interdependencies between technologies remain present, as evidenced by financial and technical indicators.

An example of this interdependency is the inverse relationship between power system inertia and renewable energy generation (Ratnam et al., 2020). In traditional power systems dominated by sources like coal, nuclear and hydro, inertia is a built-in element and when power imbalances occur, generators maintain synchronism, preventing the risk of collapse and blackouts. In contrast, renewable-based systems provide low or no inertial response, which leaves the power system exposed to frequency imbalances, thus posing an energy security risk.

Another example of this interdependency is seen in the operational hours and profitability of conventional and non-conventional generators, such as renewable energy plants. As the latter increase production, the former produce less, deliver less and obtain a lower revenue stream. However, in peak demand situations, conventional generators are still required. The impact can be self-reinforcing, as decreasing profitability may prevent investments – or even incentivise divestments - in infrastructure that remains critical to energy security.

Similarly, early retirement of infrastructure may create or aggravate energy security issues. Consider for example the transition to electricity-based passenger transportation (EVs) vs. conventional transportation. As the transition progresses and EV usage becomes more widespread, fossil fuel stations will still be required for an important fraction of the drivers, even if the distribution network is no longer profitable.

A similar situation may happen if the early retirement of energy infrastructure takes place before an alternative is in place or is sufficiently developed to support the specific transition.

An instance of this situation occurred in China in 2017, after implementation of an action plan to prevent and control air pollution (Zhou, 2018). The plan entailed both coal power plant retrofitting as well as coal-to-gas switching of 'dispersed coal' boilers that provided industrial steam, process heat, and residential heating in Northern China. However, the plan ultimately triggered a natural gas crisis, because there were not enough natural gas supplies during the winter season. The crisis led to a 30% increase in prices, a 15% spike in natural gas demand, as well as a 45% rise in LNG imports and 19% uptick in pipeline gas imports. The underlying issue was that China lacked adequate seasonal storage facilities to manage the substitution of fuels.

Europe has its own example of risky technology transition. Germany had decided to stop coal mining and coal fired power generation to comply with national climate targets. This decision rendered the country highly dependent on a single fuel for power generation, namely natural gas from Russia. With the outbreak of hostilities in Ukraine and the cessation of Russian gas deliveries to Europe, Germany had to revise its decision to ensure energy security. The German government decided to temporarily prolong coal-fired generation and has allowed a short-term expansion of coal-mining activities by a major electricity producer, as part of its efforts to reduce gas demand and thereby tackle the ongoing energy crisis.

Under the status quo, the risk of an uncoordinated transition is minimal because it is essentially perpetuating the existing state of affairs. In this scenario, there is little change, and therefore, any potential disruptions or tensions are negligible. This is because the status quo represents a continuation of the same energy systems and practices that have been in place for some time.

However, the picture changes significantly when we consider the electrification of society as the driving force behind the energy transition. Electrification, with its potential to replace traditional fossil fuel-based technologies, represents a profound and disruptive transformation. It is likely to create tensions and challenges, particularly in sectors heavily reliant on fossil fuels, such as the automotive and energy industries. This transition could lead to economic and political friction as vested interests clash with emerging technologies and industries.

On the other hand, if the energy transition is guided by a carbon offset pathway, the tensions are expected to be relatively lower. This is because a carbon offset pathway provides a structured and collaborative approach to reducing emissions. It encourages the development and adoption of clean and sustainable energy sources while offsetting emissions through various means, such as reforestation or carbon capture technologies. Such a pathway can help smooth the transition by offering alternatives and incentives to industries and regions heavily reliant on fossil fuels, thereby reducing the potential for conflicts.

Proposed metrics, China and EU

To assess the presence of this risk, the following metrics can be considered:

- Sharing of fossil and clean technologies in the overall energy technology portfolio. This can mitigate the price spikes that make the transition more costly.
- Volatility in the intra seasonal capacity factor. For gas-fired generation, low-capacity factors can be expected during the summer and high-capacity factors during the winter. Conversely, for renewables such as solar PV, a high-capacity factor can be expected during the summer and a much lower one during the winter period.

Mitigation measures, China and EU

To mitigate this risk, some of the following measures can be implemented:

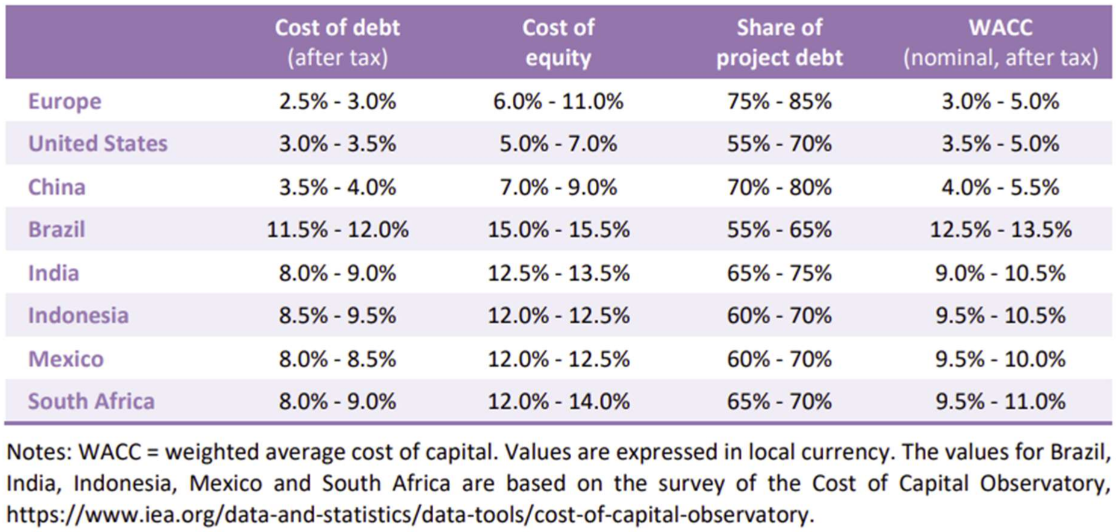
- Develop a phase-in and phase-out plan focusing on specific metrics.
- Prolong the use of existing energy infrastructure.
- Model the mid-transition and evaluate intermediate scenarios.
- Synchronise the scaling up of green fuels and technologies with the scaling down of fossil fuel infrastructure.

3.4 Cost of capital risk

The transition demands significant upfront investments, not only in Europe or China but also in India, Indonesia, Brazil, Mexico, South Africa, etc.

In September 2022, the *Cost of Capital Observatory* was launched by the IEA, the World Economic Forum, ETH Zurich and Imperial College London to increase the visibility and availability of data on financing costs in the energy sector and to inspire investor confidence (IEA, 2023c). Table 3.4, which depicts the weighted average cost of capital of utility-scale solar PV projects, shows that the weighted average cost of capital (WACC) is low and very similar in China and the EU (and the US). Therefore, the cost of capital is not considered to be a significant risk. However, WACC is two or three times higher in emerging markets and developing economies than in advanced economies and China. For example, rising borrowing costs are complicating Indonesia's energy transition plans (Suroyo & Suleiman, 2023).

Table 3.4: Indicative Weighted Average Cost of Capital for Utility-Scale Solar PV Projects, 2021



	Cost of debt (after tax)	Cost of equity	Share of project debt	WACC (nominal, after tax)
Europe	2.5% - 3.0%	6.0% - 11.0%	75% - 85%	3.0% - 5.0%
United States	3.0% - 3.5%	5.0% - 7.0%	55% - 70%	3.5% - 5.0%
China	3.5% - 4.0%	7.0% - 9.0%	70% - 80%	4.0% - 5.5%
Brazil	11.5% - 12.0%	15.0% - 15.5%	55% - 65%	12.5% - 13.5%
India	8.0% - 9.0%	12.5% - 13.5%	65% - 75%	9.0% - 10.5%
Indonesia	8.5% - 9.5%	12.0% - 12.5%	60% - 70%	9.5% - 10.5%
Mexico	8.0% - 8.5%	12.0% - 12.5%	60% - 70%	9.5% - 10.0%
South Africa	8.0% - 9.0%	12.0% - 14.0%	65% - 70%	9.5% - 11.0%

Notes: WACC = weighted average cost of capital. Values are expressed in local currency. The values for Brazil, India, Indonesia, Mexico and South Africa are based on the survey of the Cost of Capital Observatory, https://www.iea.org/data-and-statistics/data-tools/cost-of-capital-observatory.

Source: IEA (2023a).

3.5 Geopolitical risks and trade conflicts

Dependence on a small number of countries for critical minerals and challenges in diversifying supply chains may lead to geopolitical tensions and trade conflicts.

3.5.1 Trade risks - carbon leakage tariffs

The transition of one country's energy system into a renewable based system may cause trade issues with countries at a different stage of transition that still rely on fossil fuels with either an absence of or minimal CO_2 restrictions. For many years, the EU has struggled with perceived 'carbon leakage', a problem that occurs when EU producers heavily regulated by schemes such as the EU Emissions Trading System (EU ETS) cannot compete with cheaper, more carbon-intensive goods manufactured outside the EU. Trade risks might arise from measures such as tariffs aimed at reducing carbon leakage, for example the EU's CO_2 border tax which targets imports from countries with less stringent CO_2 regulations. There is also potential for retaliatory actions, for example China's proposed export restrictions on crucial minerals vital for the green technology shift.

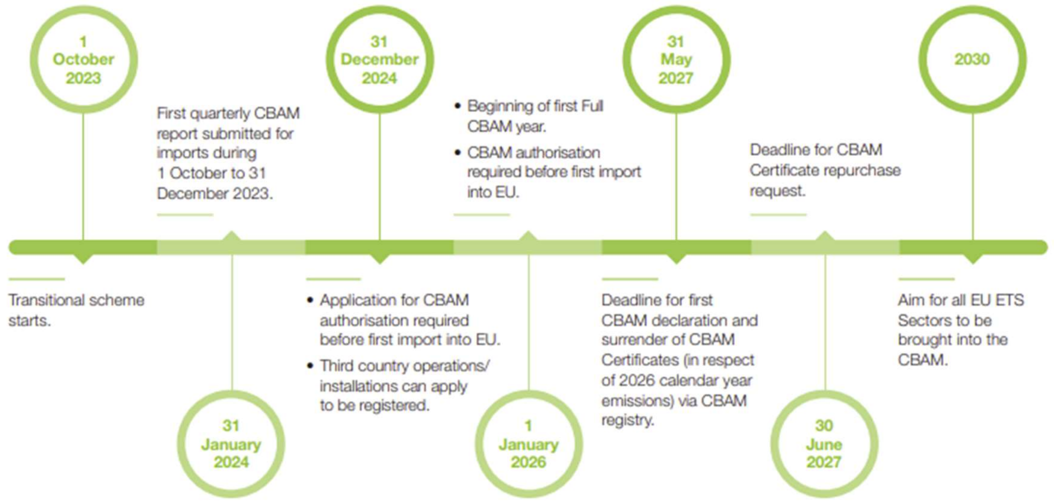
As an example, China’s ETS (Emissions Trading System) delivers a carbon price that is substantially lower than that of the EU. In 2022, the price was EUR 7 per metric ton, far below the EU’s average 2022 EUR 81 per metric ton. Part of the explanation could be that marginal cost of reducing CO_2 is lower in China than in the EU. In addition, the overall Chinese ETS system is currently limited to encompass the power sector alone, although China has regional ETS markets that cover more sectors.

To solve the issue, the EU has adopted a Regulation establishing a Carbon Border Adjustment Mechanism (CBAM) to deal with the ‘carbon leakage’ that impedes the EU’s decarbonisation plans (European Parliament & Council of the European Union, 2023). It is part of the Commission’s ‘Fit for 55’ initiative published in July 2021 that will help to achieve the EU’s target for a 55% reduction in greenhouse gas (GHG) emissions by 2030 (against 1990 levels).

The CBAM is intended to prevent carbon leakage by imposing an emissions-based levy on imports to EU of carbon-intensive products (such as cement, electricity, fertilisers, iron, steel, aluminum, and hydrogen), thereby aiming to maintain the competitiveness of EU production in carbon-intensive sectors.

In October 2023, the CBAM tariff will come into effect throughout the EU (see Figure 3.10). In its initial transition period, companies will have to report their carbon emissions but will not incur any costs. However, from 2026, they will be required to purchase a CBAM certificate for their emissions, with the certificate price being equivalent to the EU ETS price, likely to be around EUR 100 per metric ton of CO_2 (Farrell, 2023). Where emissions relating to a product have already been subject to a carbon price in a third country, through a tax or emissions trading system, a discount may be claimed.

Figure 3.10: Timeline for the EU CBAM



Source: Clifford Chance, 2023.

China’s official position is to oppose the CBAM as a unilateral measure that the country views effectively as a trade barrier. The introduction of CBAM could have far-reaching consequences for China. In 2022 the CBAM sectors accounted for 3.2% of total Chinese exports to the EU, but if CBAM is extended to other sectors, the tax could affect over 9.7% of exports to the EU and 132 types of goods.

The EU does need to provide clarification for China's export industries to explain whether a Chinese company will be eligible for reduced CBAM obligations by submitting evidence of green power consumption or green certification. Experts at the *Oxford Institute for Energy Studies* criticise the EU's lack of transparency and the risk of double counting green certificates (Hove & Xie, 2023). However, as recently shown in the August 2023 green certificate policy, China's energy regulators are working to enhance the country's green power trading and green certificate schemes. A recent report from Clifford Chance (2023) points out that the EU needs to provide more detail on CBAM, not just for Chinese exporters but for a number of nations that have voiced concerns about the new tax.

Despite the disquiet, not just in China, but among many of the EU's trading partners, there are also grounds for optimism: CBAM brings with it the prospect of future cooperation on carbon markets between the EU and China. CBAM has the potential to be transformative for China's industries and to be instrumental in China's achievement of its carbon peaking goals. The carbon tax is likely to foster domestic technological innovation in China, and encourage companies to be more innovative and efficient, as well as to prioritise renewable energy in order to reduce their CBAM exposure.

3.5.2 Geopolitical risks - national industrial boosting of clean energy

As countries seek to secure supply chains, create jobs, and boost clean energy, industrial policy is bringing risks of trade conflicts. Trade conflicts impact the free exchange of important commodities for the green transition, e.g. the 2022 inflation Reduction Act (IRA) in the US offers generous 'Made in America' subsidies, and has sparked a quick response from the EU (European Parliament, 2023).

The largest global economies are now rapidly investing in green energy production and decarbonisation. These economies have realised that support for transition policies is seen as critical for self-sufficiency and dominance of the future energy market. Some economies such as China and Europe have been investing heavily in clean technologies over the past decade. The latest participant in the clean energy race is the US.

The 2022 IRA is a landmark American legislative package aimed primarily at bolstering domestic clean energy production. In recent months, it has sparked some controversy regarding the open trade consequences of its generous 'Made in America' subsidies.

The EU is concerned about the IRA because it threatens Europe's share of the global clean energy market and will attract companies to invest in the American economy rather than Europe. For these reasons, in February 2023, the European Commission presented a new energy plan that updates the existing NextGenerationEU (COVID recovery) plan to protect the EU green industry from the IRA. The IRA includes subsidies for producers of carbon-neutral electricity, including energy production with CCS – encompassing natural gas or hydrogen production with CCS – as well as nuclear energy Furthermore, the legislation encourages the capture of industrial CO_2 emissions. It offers a tax credit of USD 35 to USD 60 per ton when captured CO_2 is used to produce low and zero-carbon fuels, chemicals, building materials, and other products.

The EU *Green Deal Industrial Plan* is the latest energy plan to update the so-called European Green Deal. Published by the European Commission on 1 February 2023, it is a direct response to the IRA. The European plan will extend support for renewable technologies, as well as renewable hydrogen and biofuel storage. Further, it will enhance investment support schemes for the production of strategic carbon-neutral technologies and provide more precise aid targets for major new projects in strategic net-zero production value chains (European Commission, 2023e).

3.6 Dependence of clean energy technologies on critical raw materials

Critical raw materials

Since renewables are far more material-intensive than conventional energy technologies, the decarbonisation of the energy system is highly dependent on critical raw materials, such as lithium, nickel, cobalt, copper, and rare earth elements. Critical materials are essential for a range of clean energy technologies, such as solar PV, wind, hydropower, battery storage, and hydrogen. However, market dynamics, geopolitics and supply shortages present risks to supply chains. In order to identify and handle these risks, the US, the EU, and China, among others, assess and label critical materials. However, experts warn that this labelling 'serves to legitimise the exceptional use of state power and resources to ensure sustainable access to and/or protected exploitation of those raw materials' (Andersson, 2020).

In 2019, European Commission proposed the Critical Raw Materials Act to strengthen domestic supply chains and to develop mutually beneficial partnerships with third countries (European Commission, 2023a). The EU identified high dependence on China for raw materials relating to technologies such as electrolysers, components for wind turbines and magnets for electric motors, and materials for the entire photovoltaic value chain (Carrara et al., 2023). Similar to the EU's critical raw materials list, China's State Council published a National Mineral Resources Plan (2016-20) and a catalogue of 'strategic minerals' in 2016, which it intends to update every five years. Among other measures, the plan proposes a monitoring and early warning mechanism for strategic minerals, for example, to be able to issue early warnings on resource security during major international conflicts.

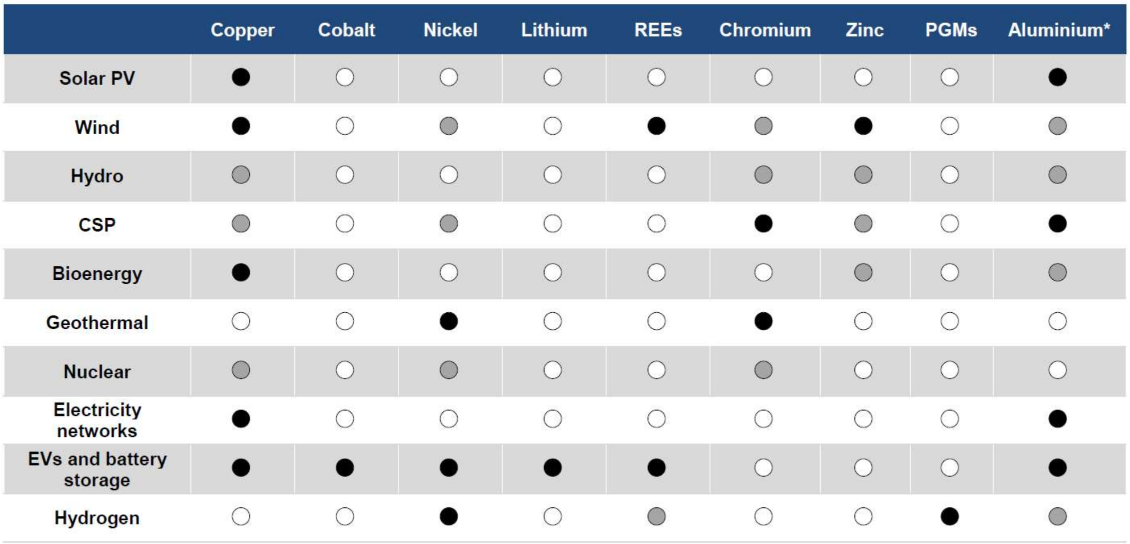
In July 2023, China's Ministry of Commerce announced that export controls would be imposed on gallium and germanium-related items, which may impact the supply of semiconductor materials for the solar PV industry, starting from 1 August 2023 (MOFCOM, 2023). This action from China could be seen as a countermeasure to US restrictions on the export of microchips to China.

To ensure the availability of the resources needed to decarbonise the energy sector, it is reassuring to see that governments are increasingly aware of the vulnerability of critical commodity supply chains. However, constructive engagement, improvements to fair trade practices, and strengthened powers for the World Trade Organisation (WTO) are essential to ensure a reliable supply chain for the clean energy technologies needed to decarbonise the global economy.

Dependence of clean energy technologies on critical raw materials in China and the EU

The transformation of energy systems entails a transition from fuel-intensive supply chains to material-intensive ones. Countries and industries that produce the necessary minerals and metals therefore serve as important links between the resources in the ground and many of the energy technologies required for the green transition. However, the mismatch between rapidly growing demand and lagging supplies gives rise to volatile prices, which tend to exhibit even greater fluctuations than those observed in hydrocarbon markets. Added to this, raw materials supply chains tend to be more opaque and are characterised by fewer dominant players. Figure 3.11 maps some of the critical raw materials to a selection of low-carbon technologies (IEA, 2022c).

Figure 3.11: Critical mineral needs for clean energy technologies



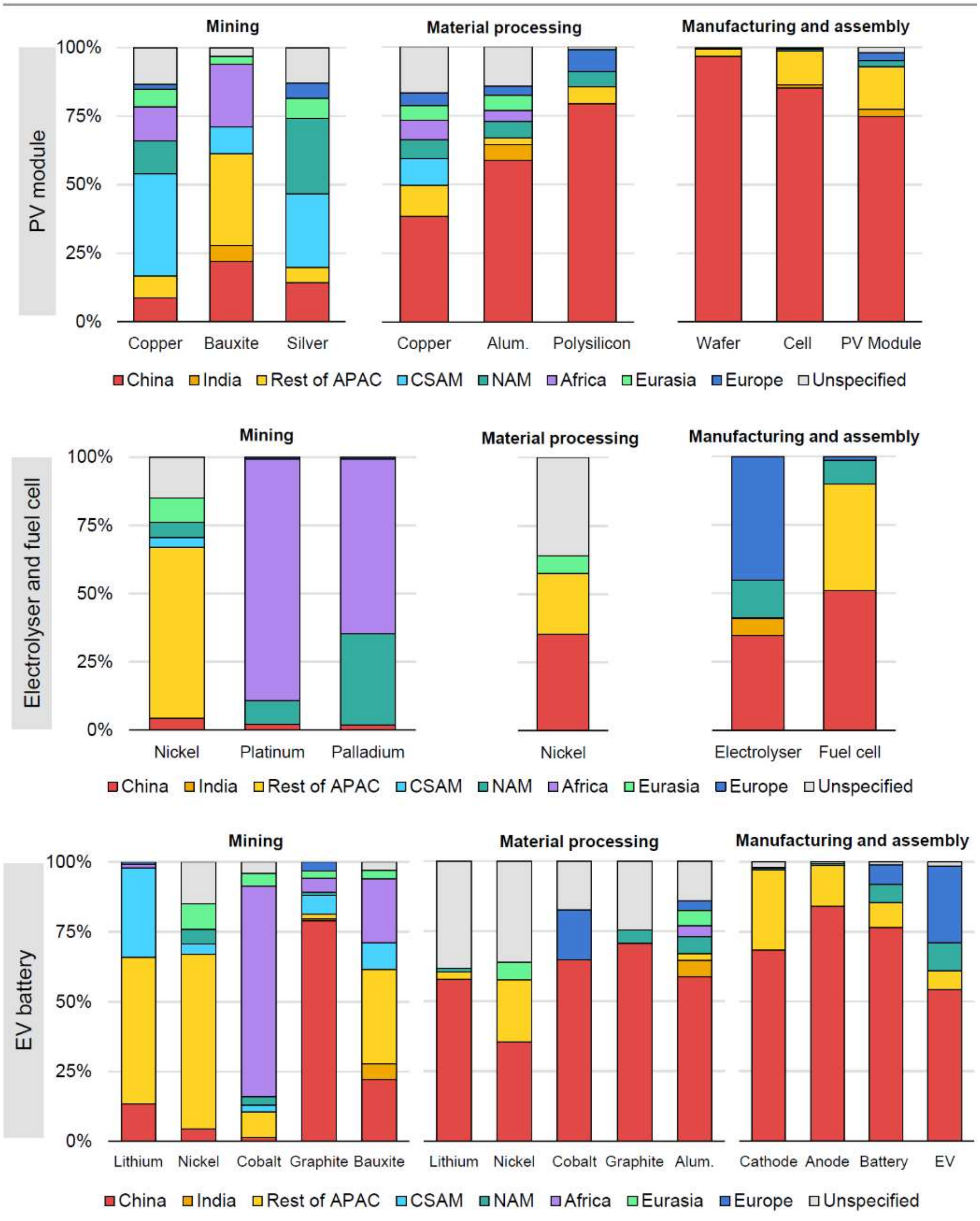
	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	◍	○	●	◍	●	○	◍
Hydro	◍	○	○	○	○	◍	◍	○	◍
CSP	◍	○	◍	○	○	●	◍	○	●
Bioenergy	●	○	○	○	○	○	◍	○	◍
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	◍	○	◍	○	○	◍	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	◍	○	○	●	◍

Source: The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report, (IEA, 2022c).

Notes: *CSP = concentrating solar power; PGM = platinum group metals. Shading indicates the relative importance of minerals for a particular clean energy technology (dark = high; grey = moderate; no shading = low).*

However, relative to many other countries that depend on critical materials to transform their energy systems through the adoption of clean energy technologies, China's position is rather advantageous. As Figure 3.12 and Figure 3.13 show, China is a major player in several clean energy technology supply chains such as EV deployment, PV systems, wind and electrolyser installations - particularly in the mid- and downstream levels.

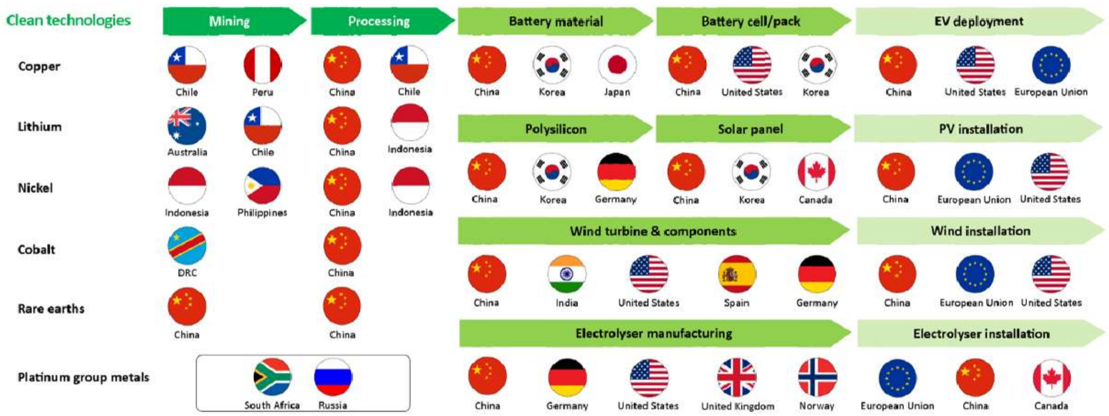
Figure 3.12: Geographic concentration of selected clean energy technologies by supply chain stage and country/region, 2021



Source: IEA.

Notes: *NAM: North America; Rest of APAC: Asia-Pacific excluding China and India; CSAM: Central and South America. Alum: Aluminium. Although Indonesia produces around 40% of total nickel, little of this is currently used in the EV battery supply chain. The largest Class 1 battery-grade nickel producers are Russia, Canada, and Australia. Sources: Securing Clean Energy Technology Supply Chains (IEA, 2022b)*

Figure 3.13: Indicative supply chains for selected clean energy technologies



Source: World Energy Outlook. (IEA, 2023b).

In the solar PV industry, China has modest mining capacities (e.g. 8% for copper) but major processing capabilities (e.g. 80% of total polysilicon processing capacity) and it holds a clearly dominant position in the manufacturing and assembly stage (e.g. 95% of wafer, 88% of cells and 75% of PV modules). A similar conclusion can be reached on the electrolyser and fuel cell industry, where China produces at least 33% of all electrolysers and 50% of fuel cells globally. In the EV industry, China's position is particularly strong at the mining stage, with approximately 80% of graphite capacity, and significant processing capacities for nickel, cobalt, and graphite. Further, China dominates the manufacturing and assembly of cathodes, anodes, batteries and EVs (IEA, 2022b).

Under the status quo, this supply chain advantage presents a rather neutral risk for China, as its energy transformation is not directly dependent on the availability of critical materials. Similarly, if China's transition pathway is dominated by carbon offsetting technologies, China has a perceived low risk on the availability of critical materials.

In contrast, if China's pathway to carbon neutrality relies on renewable technologies, the perceived risk is relatively higher both in the mid-transition and in the fully decarbonised future. The rationale behind this assessment is that despite China's comparative advantage, the mere fact of China opting for a renewable-based pathway to carbon neutrality will increase competition for resources, as its footprint on the global market is substantial.

In the mid-transition, this risk could materialise and compromise the speed of China's energy transformation as supply-chain bottlenecks become more prevalent. On the other hand, understanding China's favourable risk position presents an opportunity to enhance China's industrial development in these critical activities for the global energy transformation.

Risk evaluation, China

Based on Figure 3.12 and Figure 3.13, the general future risk for China is assumed to be neutral to moderate.

Risk evaluation, EU

In contrast to China, Europe has a modest role in the clean energy supply chains for critical materials (see Figure 3.12 and Figure 3.13). Europe's importance is mainly downstream: manufacturing and assembly of electrolysers, EV batteries and PV and wind installations. Compared to China in all comparable scenarios, the risk for Europe is assessed to be at least the same, with a tendency to be larger than for China. This is based on China's advantages with regard to supply chains. However, China may in some areas face greater challenges than Europe because of lower development status and complicated geopolitics.

Proposed metrics, China

The assessment of this risk can include the following indicators:

- Share of Chinese/European mid and downstream (mineral refining, assembly, and distribution) capacity in the global market for each relevant supply chain, including battery cells, EV batteries and other lithium-ion batteries.
- Import dependence (share and source of imports) on raw materials which are critical to the mid- and downstream supply chains.

Proposed metrics, Europe

The assessment of this risk can include the following indicators:

- Import dependence (share and source of imports) on raw materials which are critical to all stages of supply chains.

Mitigation measures, China

Risk mitigation measures for China include:

- A dedicated effort to surveying and exploring the availability of critical materials in China.
- Direct investment in overseas sources of critical materials.
- Expansion of the mid- and downstream in the critical materials supply chain through the establishment of contracts and long-term agreements.
- Investing in the development of alternative technologies which reduce or avoid the need for critical raw materials.

Mitigation measures, EU

Risk mitigation measures for the EU include:

- Direct investment in overseas sources of critical materials.
- Expansion of the critical materials supply chain through the establishment of contracts and long-term agreements.
- Investing in the development of alternative technologies which reduce or avoid the need for critical raw materials.

3.7 Cyber-attacks/IT risks

The energy transition, leading to a more electrified, digitally connected smart grid, amplifies its vulnerability to cyber-attacks, highlighting a significant IT risk.

Digitalisation can accelerate the clean energy transition by unlocking increased demand-response opportunities, integrating higher shares of VRE, and enabling the intelligent balancing of power supplies and demand such as via smart charging of electric vehicles. At the same time, increased connectivity, IoT (Internet of Things), smart meters and automation may increase the security risks of cyber-attacks on power systems.

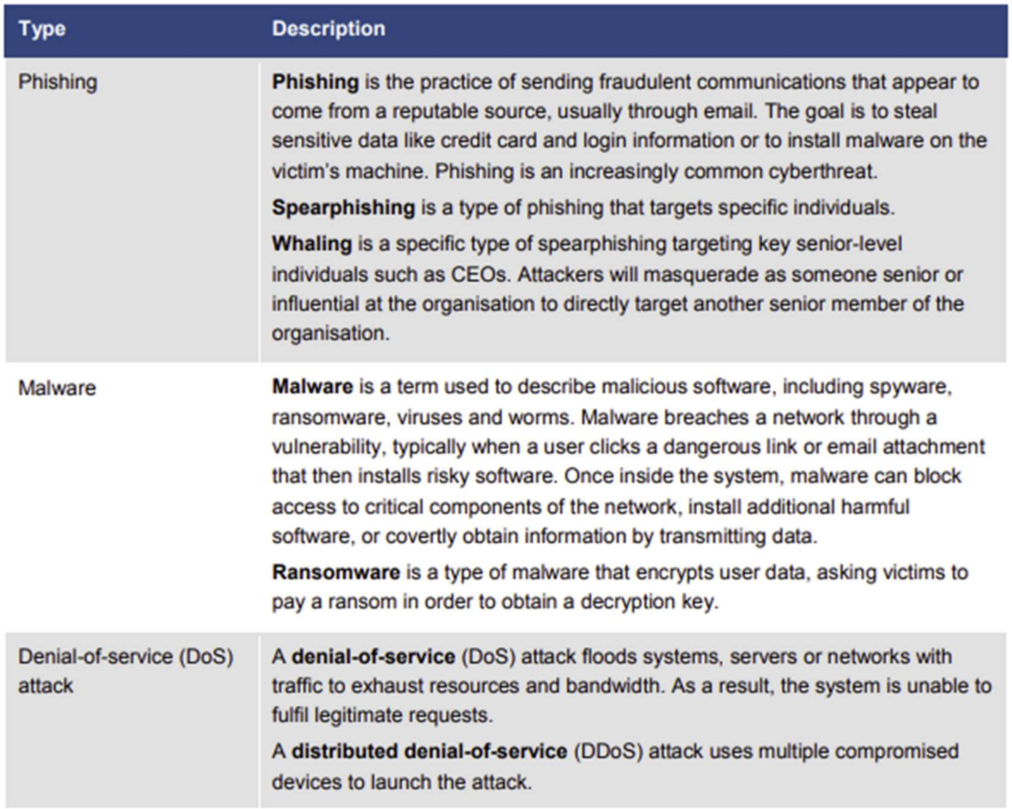
Cyber-attacks are becoming more and more difficult to withstand. A successful cyber-attack can trigger the loss of control over devices and processes and cause large-scale, lengthy service disruptions.

The majority of attempted attacks are phishing email attacks which are in general the easiest types of cyber-attack to defend. Other common attack types include malware and denial-of-service attacks.

Table 3.5 and Table 3.6 (IEA, 2021a) describe the following cyber security issues:

- common types of cyber-attacks on IT systems.
- opportunities and cyber risks from digitalisation across the electricity value chain.

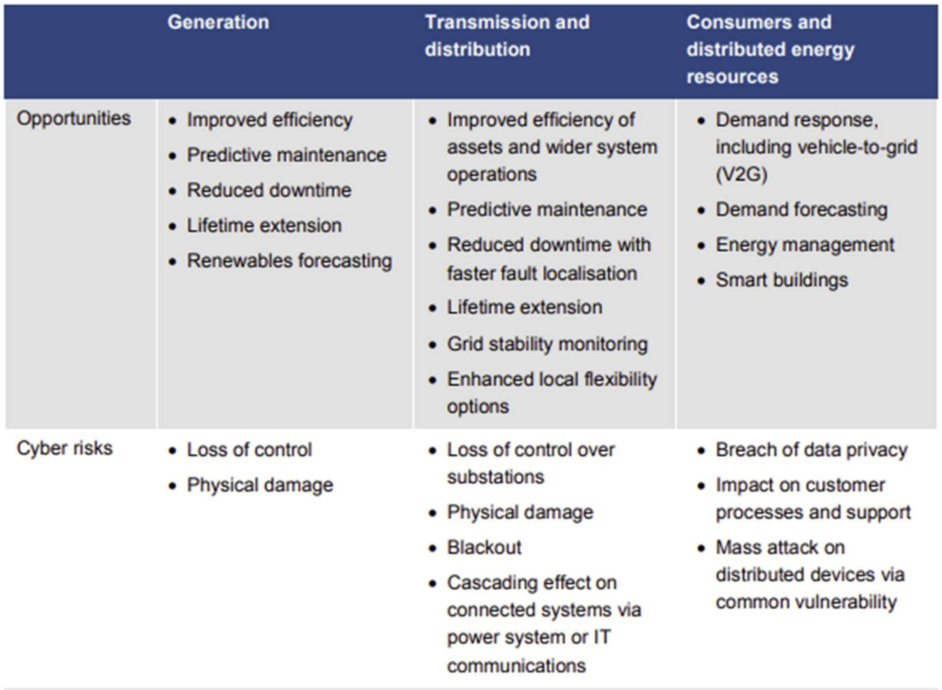
Table 3.5: Common Types of Cyber-Attacks



Type	Description
Phishing	**Phishing** is the practice of sending fraudulent communications that appear to come from a reputable source, usually through email. The goal is to steal sensitive data like credit card and login information or to install malware on the victim's machine. Phishing is an increasingly common cyberthreat. **Spearphishing** is a type of phishing that targets specific individuals. **Whaling** is a specific type of spearphishing targeting key senior-level individuals such as CEOs. Attackers will masquerade as someone senior or influential at the organisation to directly target another senior member of the organisation.
Malware	**Malware** is a term used to describe malicious software, including spyware, ransomware, viruses and worms. Malware breaches a network through a vulnerability, typically when a user clicks a dangerous link or email attachment that then installs risky software. Once inside the system, malware can block access to critical components of the network, install additional harmful software, or covertly obtain information by transmitting data. **Ransomware** is a type of malware that encrypts user data, asking victims to pay a ransom in order to obtain a decryption key.
Denial-of-service (DoS) attack	A **denial-of-service** (DoS) attack floods systems, servers or networks with traffic to exhaust resources and bandwidth. As a result, the system is unable to fulfil legitimate requests. A **distributed denial-of-service** (DDoS) attack uses multiple compromised devices to launch the attack.

Source: IEA (2021a).

Table 3.6: Opportunities and Cyber Risks From Digitalisation Across the Electricity Value Chain

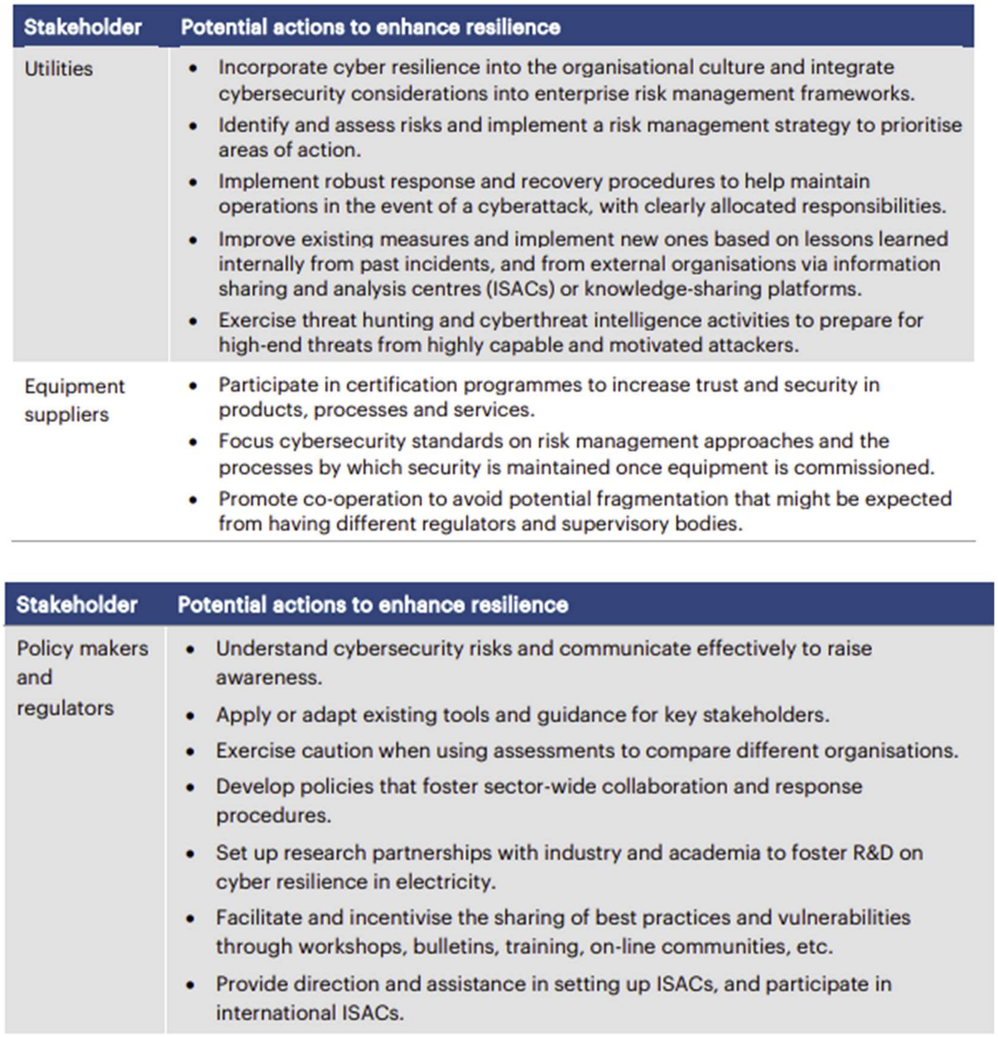


	Generation	Transmission and distribution	Consumers and distributed energy resources
Opportunities	• Improved efficiency • Predictive maintenance • Reduced downtime • Lifetime extension • Renewables forecasting	• Improved efficiency of assets and wider system operations • Predictive maintenance • Reduced downtime with faster fault localisation • Lifetime extension • Grid stability monitoring • Enhanced local flexibility options	• Demand response, including vehicle-to-grid (V2G) • Demand forecasting • Energy management • Smart buildings
Cyber risks	• Loss of control • Physical damage	• Loss of control over substations • Physical damage • Blackout • Cascading effect on connected systems via power system or IT communications	• Breach of data privacy • Impact on customer processes and support • Mass attack on distributed devices via common vulnerability

Source: IEA (2021a).

A large number of management tools, security frameworks, technical measures and self-assessment approaches are available to help improve cyber resilience. In cooperation with regulators and other authorities, industries need to apply what is relevant in their context and approach resilience as a continuous process rather than a one-time milestone (IEA, 2021a). Table 3.7 shows potential actions to enhance cyber resilience (IEA, 2020).

Table 3.7: Overview of Actions to Improve Cyber Resilience



Stakeholder	Potential actions to enhance resilience
Utilities	• Incorporate cyber resilience into the organisational culture and integrate cybersecurity considerations into enterprise risk management frameworks. • Identify and assess risks and implement a risk management strategy to prioritise areas of action. • Implement robust response and recovery procedures to help maintain operations in the event of a cyberattack, with clearly allocated responsibilities. • Improve existing measures and implement new ones based on lessons learned internally from past incidents, and from external organisations via information sharing and analysis centres (ISACs) or knowledge-sharing platforms. • Exercise threat hunting and cyberthreat intelligence activities to prepare for high-end threats from highly capable and motivated attackers.
Equipment suppliers	• Participate in certification programmes to increase trust and security in products, processes and services. • Focus cybersecurity standards on risk management approaches and the processes by which security is maintained once equipment is commissioned. • Promote co-operation to avoid potential fragmentation that might be expected from having different regulators and supervisory bodies.

Stakeholder	Potential actions to enhance resilience
Policy makers and regulators	• Understand cybersecurity risks and communicate effectively to raise awareness. • Apply or adapt existing tools and guidance for key stakeholders. • Exercise caution when using assessments to compare different organisations. • Develop policies that foster sector-wide collaboration and response procedures. • Set up research partnerships with industry and academia to foster R&D on cyber resilience in electricity. • Facilitate and incentivise the sharing of best practices and vulnerabilities through workshops, bulletins, training, on-line communities, etc. • Provide direction and assistance in setting up ISACs, and participate in international ISACs.

Source: IEA.

3.8 Escalation of tensions between wealthy and poorer countries

The transition to cleaner energy sources could potentially strain relationships between wealthier and less affluent nations if the pledged climate assistance is not delivered. For instance, during the 2022 UNFCCC conference in Egypt, developing countries accused richer nations of failing to offer promised climate assistance.

Wealthier countries should provide funding for the energy transition of developing nations and emerging economies due to historical emissions responsibility and their greater economic capacity. This support is crucial for achieving global climate targets and preventing emissions leakage. Additionally, it promotes stability, reduces vulnerabilities, and fosters technological innovation worldwide.

3.9 Technology risk

The implementation of certain technologies such as CCUS and P2X are necessary but so far unproven on a large scale. The technology risk could lead to adverse effects, such as extension of fossil fuel dependency, higher energy consumption or less efficiency.

Uncoordinated technology risk

The pace at which the phase-in/phase-out of technologies takes place is risky, as there is no objective method to determine the best timing and speed of such processes. For example, the phasing-in of new technologies such as wind and solar must be balanced with the phasing-out of fossil-fuelled generation. If fossil-fuelled generators are phased out too quickly, critical security issues may arise due to lack of capacity during peak demand and/or hours with low renewable generation.

The phasing out of fossil-fuelled generators can be prompted by lower profits now that cheaper renewable generation is accounting for an ever larger amount of total electricity supplied over the year. This is happening right now in Europe, with some countries forced to introduce capacity mechanisms and so pay separately to ensure capacity is available.

Technology risk

The ECECP project ‘Investment and Technologies for Net-Zero Carbon Infrastructure’ concluded that while CCS, CCUS and P2X technologies exist, most are still at the prototype and demonstration phase (ECECP, 2023). Large-scale commercial implementation and applications are very limited. Therefore, there is a technological (and economic) risk that the technologies will not deliver the expected results.

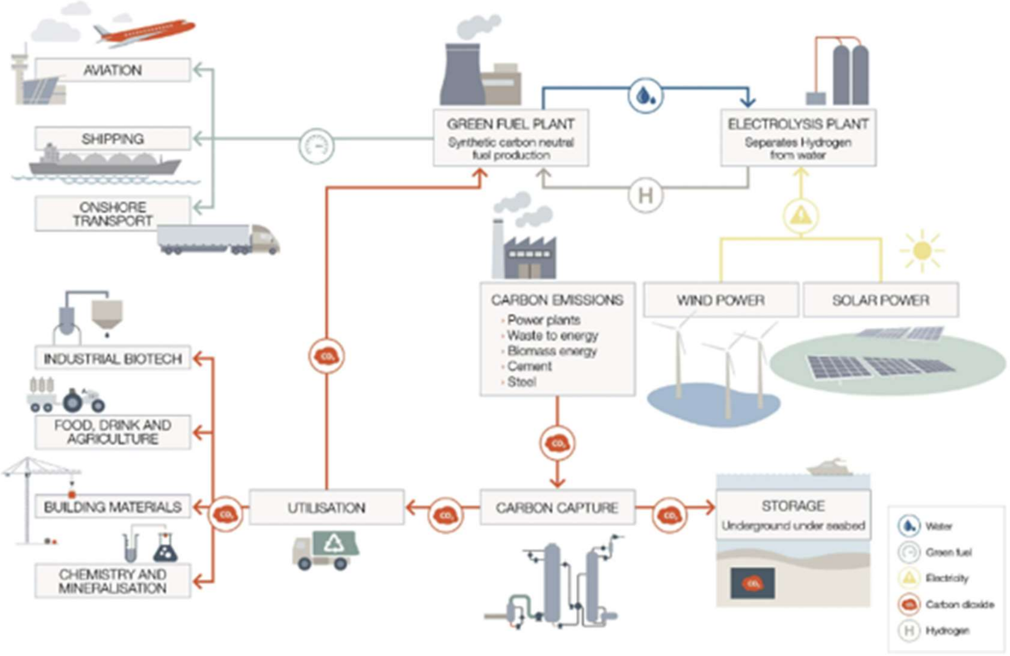
P2X can technically be used almost anywhere but process inefficiencies and limited suitable (biogenic) CO_2 sources means that P2X should be reserved for hard-to-abate sectors, such as steel, concrete, shipping, aviation and heavy road transport.

CCS and P2X technologies are expensive and energy intensive and therefore are likely to increase energy prices and total energy consumption at least until the technology becomes more efficient. The conversion losses today for producing green hydrogen and green e-fuels amount to between 40% and 55%, with future improvement likely. Still, the conversion losses are likely to remain high, to the order of about 40%.

It Is important to note that elec”Iic’ty-based fuels only contribute to climate protection if additional renewable generation is installed to supply the necessary energy input to the process or if the CO_2 emissions from the power system supplying the P2X process are extremely low.

Figure 3.14 illustrates the interdependencies between technologies for CCS, CCUS, electrolysis and green e-fuels.

Figure 3.14: CCUS and P2X - overview (COWI, 2023)



Source: COWI (2023).

3.10 Climate change impact risk

Renewable generation technologies are influenced by climatic changes, and other generation technologies may be affected by factors like water availability and temperature.

Many countries have ambitious targets moving towards carbon and climate neutrality. Achieving this requires a transformation of energy infrastructure, planning and regulation. It is evident that future energy infrastructure development and operations need to be more coordinated between energy carriers and sectors. With the consensus for a high share of VRE and electrification as the crux of decarbonisation, as well as the need for P2X and CCS as key technologies for hard-to-abate consumption, new challenges for the power system arise: how to integrate the high share of VRE while ensuring system adequacy with very low fossil-based generation?

Progress on the clean energy pathway is being led by the electricity sector due to heavy cost reductions of especially solar PV and wind power. These generation sources are central to electrification, hydrogen production and future P2X facilities and thereby the clean energy transition.

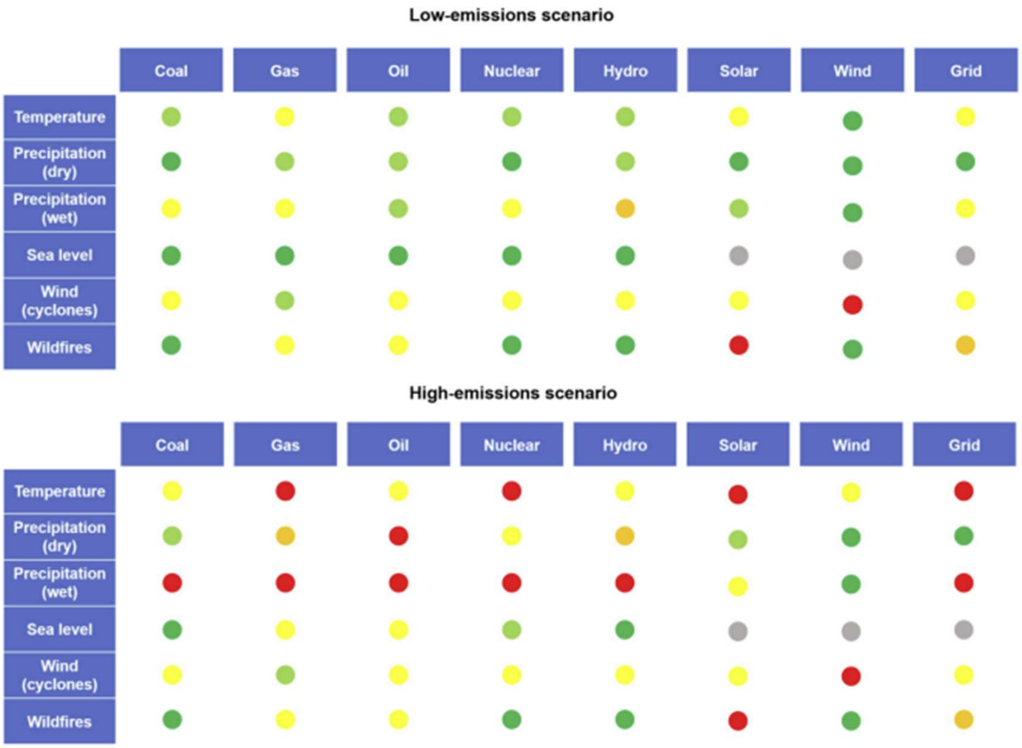
In the transformation of energy systems, the IEA (2021) points to a number of principles for ensuring energy security:

- Prioritise energy efficiency.
- Secure integration of wind and solar PV in power systems. Ensure best use of existing sources of flexibility in power systems and enable effective smart grids and digitalisation.

- Develop and deploy a portfolio of low-carbon generation sources to increase diversity of power supply and hedge against technology risks.
- Ensure the cost-effective use of existing energy infrastructure for an affordable, secure, and clean energy pathway.
- Modernise oil security systems and promote transparent, open, and competitive energy markets to accommodate traditional and emerging energy security concerns.
- Prepare for new and emerging risks to energy security. Boost the resilience of global supply chains including for critical minerals. Foster digital security and climate resilience of energy infrastructure.
- Promote a people-centered and inclusive approach to ensure energy access and reduce poverty, and foster economic diversification in producer economies.

The IEA (2022) report *Climate resilience for Energy Security* provides a comprehensive overview of climate change risks to power systems. An overview is provided in Figure 3.15.

Figure 3.15: Comparison of climate change risks to power systems in the low-emissions and high-emissions scenarios, 2080-2100



Source: IEA (2022).

Figure notes:
In the figure, levels of climate risks are divided into five categories, from dark green for low risks to red for high risks. Grey cells indicate no information. The levels are determined based on the combination of hazard, exposure, and vulnerability. Hazard and exposure are calculated through GIS analysis, while vulnerability is determined through qualitative research.
For temperature, the level of exposure of power plants and grids to the increase in mean temperature and the number of days with maximum temperature above 35°C data is used.
For precipitation (dry), the level of exposure of power plants and grids to a drier climate based on the Standard Precipitation Index and the number of consecutive dry days is used. For precipitation (wet), the level of exposure of power plants and grids to a wetter climate based on the Standard Precipitation Index and one-day maximum precipitation is used.
For sea level, the level of exposure of power plants and grids to the projected rise of sea level is used. For wind, the level of exposure of power plants and grids to tropical cyclones based on the analysis of historical trends of tropical cyclones and major tropical cyclones (above Category 3) is used. For wildfires, the level of exposure of power plants and grids to wildfires based on the analysis of historical trends of fire weather is used.

In the energy transition, power and energy will be more and more dependent on generation from renewables. In China and Europe in particular, wind power and PV will play a dominant role. Therefore, the main focus will be on these technologies. The evaluations are based on the above-mentioned IEA report *Climate resilience for Energy Security* (IEA, 2022a).

Wind power

Climate change could mean that major wind power regions will see decreasing average wind speeds and correspondingly lower output from wind power plants. In recent years, global mean wind speed has decreased in large parts of North America and Eurasia. The downward trend could continue in the Mediterranean, northern Europe, Russia, China and Central and East Asia. However, confidence in this projection for wind speeds is low.

Extreme heat can also impact wind power generation, causing reduced technical lifetime. The increasing frequency of extreme heat events can also add stress to wind power generation.

Wind power plants are usually designed for a 25°C environment, and a standard wind turbine can work at full power in an outside temperature of up to 35°C. Higher temperatures can reduce the lifetime of battery cells and other electronic components and cause wear. Under extreme heat, such as 45°C, a standard wind turbine normally has to shut down completely. A new design is needed for high temperature environments. As an example, a new wind power plant design that can operate in temperatures of 45°C has been developed for a wind power project in Oman.[8]

PV

Heat is the most significant climate impact for solar power generation. Higher temperatures lead to a less electricity generation. PV works best in cool, sunny weather. Moreover, solar power generation efficiency degrades as the solar panel temperature increases, generally about 0.5% per degree above 25°C.

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[8] The wind power plants being installed in the Dhofar Wind Power Project in Oman have a unique design that uses angled air vents to naturally cool the structure, preventing overheating and enabling operation in temperatures up to 45 degrees Celsius. See: https://www.ge.com/news/reports/just-deserts-wind-turbine-can-handle-sandstorms-desert-sun

Extreme temperature can also increase the electrical resistance of the circuits and damage the PV cells. For example, if surface temperatures of the solar panels rise to 70°C, solar PV efficiency can drop by more than 20% if no adaptation measures and technological enhancements are undertaken.

Nuclear and fossil-fuelled power station

Nuclear is a non-carbon emitting source and is an important energy technology in the European (France) and Chinese transition of energy systems.

Fossil-fuelled power stations based on coal and natural gas will gradually have a less important role as the transition proceeds. However, they will be needed to some extent in the future as reserve and for providing system services. Some of these power stations could be fitted with CCS.

The future climate impacts will mainly be as follows:

- More frequent heavy rainfalls and floods could disrupt generation.
- Water shortage could become a growing concern for power plants that rely on wet cooling systems: already, low levels in European rivers during dry periods have led to limited generation.
- Likewise, global warming that raises the temperature of cooling water intakes will lead to lower efficiencies and reduced generation output.

Hydropower

The IEA (2022) points out that climate change could impact hydropower potential and output by changing precipitation and temperature, water availability, shifting seasonal flows and stream-flows, and increasing the risks of physical damage to assets as well as evaporation losses from reservoirs. The specifics of local geographical and climatic situations makes a global statement on the influence of climate change on hydropower difficult. Chapter 6.6 includes a discussion on current hydropower generation patterns in China and the EU. The data is unclear on hydropower from rivers and hydropower with reservoirs, as well as the use of dams not only for power generation but also for irrigation, drinking water supply, flood management, etc., making it difficult to analyse the influence of weather in this context.

Climate impacts on energy output in China and the EU

Changes in average temperature and rainfall conditions can impact the overall energy infrastructure. Power generation, electricity transmission, oil and gas and nuclear infrastructure may be affected by the increased frequency of changing environmental conditions. The effects may be sudden and severe with impacts materialising without notice, but may also be progressive and observable over longer periods of time.

Power generation technologies – both conventional and renewable – are exposed to climate impacts (Burillo, 2018). Increased air temperatures may decrease the generation efficiency of thermal power plants and may also reduce the capacity of lines and transformers. Renewable energy output becomes more uncertain, as medium- and long-term changes in the availability of natural resources such as water, sunshine and wind materialise.

The risks arising from the water-energy nexus are also relevant (Rodriguez & Madrigal, 2014). For example, thermal power plants may be forced to shift to dry cooling systems instead of the more efficient water-cooled ones. Low water flows, high water temperatures and low precipitation levels may affect hydroelectric production, which is another important component of the energy systems in the EU and China.

Not only does China have the largest share of global hydroelectric generation capacity (30.1% in 2019), but it also has the largest net installed hydroelectric generation capacity in the world (356 GW) thanks in no small part to its massive
22 500 MW Three Gorges dam – the largest in the world (IEA, 2021).

Hydropower is also a key power source in Europe. According to Eurostat in 2021 it accounted for 32% of the EU’s renewable electricity production and provided 12% of the EU’s electricity (Eurostat, 2023b). One of the reasons for the tight European power market in 2022 was low energy production from hydropower due to low reservoir levels caused by low precipitation.

Of relevance for energy security is the fact that 17.4% of China’s domestic electricity generation is supplied by hydropower. It is worth noting that droughts, heavy rainfall and heatwaves are not rare occurrences in China. For example, in 2022 southern China experienced its heaviest rainfall in 60 years. Jiangxi province declared a water supply ‘red alert’ due to record low levels in its Poyang freshwater lake, and record high temperatures were reported during the summer months.

The extraction of shale oil and gas, which is yet another area of interest, particularly in China, highlights another example of the water-energy nexus, as hydraulic fracturing relies heavily on water resources. Further, water scarcity can also affect water-intensive conventional electricity generators such as nuclear power, natural gas, coal-fired power plants and a range of renewables-based technologies, such as biomass. As an example, low water levels in European rivers have in dry years constrained power generation from nuclear and fossil-fuelled power plants.

Severe weather conditions such as heatwaves and extreme cold spells can also affect demand in both Chine and EU, as these events trigger much higher electricity consumption for cooling purposes and increase heating demand during periods of extreme cold. The coincidence of extreme weather conditions can also compound risk impacts and create vicious cycles, which may potentially lead to serious energy security impacts. For example, when droughts are accompanied by heatwaves, both supply and demand are affected. Similarly, fuel sources are also interdependent, as is the case between gas, coal, and electricity.

Power outages may limit gas production and conversely, limitations in gas and coal may also impact power generation. In turn, power outages may also disrupt the water supply, which creates cascading effects.

It is projected that climate impacts may affect the overall energy system in both China and the EU regardless of the technology choice towards carbon neutrality.

Proposed metrics, China and EU

To assess the presence of this risk, the following metrics can be considered:

- Share of variable RE in total production scaled by uncertainty.
- Sources of flexibility (transmission, backup generation, demand side).
- Studies on climate change impacts and possible climate disruption in China and EU.

Mitigation measures, China

To mitigate this risk, China may implement and continue implementing some of the following measures:

- Investing in power system flexibility (e.g. transforming coal-fired plants in China to enhance flexibility for the whole electricity system).
- Enhancing sector coupling.
- Investing in adequate reserves of climate-resilient firm capacity.
- Investing in more flexible and market-integrated inter-provincial transmission.
- Investing in both short-term and seasonal energy storage technologies.
- Incentivising demand response.
- Improving the quality and frequency of renewable resource forecasting, including detailed hydrological studies.
- Improving renewable energy planning decisions (including siting) to make the best use of the ‘smoothening effect’, by which renewable energy production is geographically spread out.
- Preparing to use air-cooled systems for thermal power generation technologies, if necessary.
- Investing in less water-intensive techniques, such as hydro-fracking to extract oil and natural gas.

Mitigation measures, EU

For Europe the most relevant measures may be:

- Investing in power system flexibility e.g. transforming power plants in the EU to enhance the flexibility for the whole electricity system.
- Enhancing sector coupling.
- Investing in adequate reserves of climate-resilient firm capacity.
- Investing in more flexible and market-integrated transmission including new interconnectors between Member States.
- Incentivising demand response.

3.11 Dependency on large-scale variable renewables and weather patterns

Relying more on VRE poses security risks, especially with the influence of climate and weather patterns. **This risk is further assessed in Chapter 4.**

3.12 Summary of the energy transition risks in the EU and China – security risk metrics and mitigation measures

The examination of energy security risks has revealed that China and the EU share several common challenges, albeit with some differences. Six specific risks were further assessed for both regions due to their perceived significance and the potential for meaningful comparison. Suitable mitigation measures are summarised in Table 3.8.

- Dependence on imported fuels.
- Dependence of clean energy technologies on critical materials.
- Inflexible and inefficient demand.
- Climate impacts on energy production (renewable and non-renewable energy).
- Uncoordinated technology transition.
- Insufficient transmission system integration.

Regarding *dependency on imported fuels*, the risk is assumed to decrease over time in both China and the EU. Both have officially declared they intend to follow the transition track of large-scale deployment of renewables, especially PV and wind.

When it comes to the *dependence of clean energy technologies* on critical materials, China has a dominating role in most global technology and critical material supply chains. By contrast, the EU will be dependent on trading on the world market and on establishing long-term agreements and contracts.

Inflexible and inefficient demand. In Europe, energy markets have been implemented in the energy sector during the last two to three decades. More recently, national implementation of plans for the roll out of smart meters to end-consumers has got under way. This means that many end-consumers already have the possibility to react to energy prices and to consume less when prices are high. So, the mechanism for prices to feed through from generation to end-consumers is more developed compared to China.

Climate impacts on energy production. Climate impacts may affect the overall energy system in both China and the EU regardless of the technology choice towards carbon neutrality. The risks and mitigation measures have the same character.

The risk of *uncoordinated technology transition* is more or less the same in China and EU, as are the proposed metrics and mitigation measures.

Insufficient transmission system is a potential barrier to a green transition that includes large-scale deployment of renewables, especially solar and wind. Europe has an established planning regime for power transmission which includes sector coupling with the natural gas sector and the hydrogen sector. The planning is done within the European market framework and based on CBA. Once China has adopted a fully-fledged market approach, including a spot market, the transmission development in China can be market led and therefore more efficient.

Table 3.8: Overview of Risk Mitigation Measures

Risk	Mitigation measures China	Mitigation measures EU
Dependence on imported fuels	Increase cooperation with foreign suppliers. Diversify imports between different exporting countries. Consolidate internal supply chains for the development of synthetic fuels. Commit to a decarbonisation pathway involving renewables.	Continue the strategy of diversifying imports between different exporting countries.
Dependence of clean energy technologies on critical materials	Increase efforts to survey and explore the availability of critical materials in China. Direct investment in overseas sources of critical materials. Expansion of the mid- and downstream in the critical materials supply chains. Invest in the development of alternative technologies which reduce or avoid the need for critical raw materials.	Direct investment in overseas sources of critical materials. Expansion of the critical materials supply chain through the establishment of contracts and long-term agreements. Invest in the development of alternative technologies which reduce or avoid the need for critical raw materials.
Inflexible and inefficient demand	Adopt cost reflectiveness in all energy pricing. Adopt a decisive initiative to measure and digitise energy consumption while developing measures to incentivise consumer awareness. Create incentive mechanisms for retrofit and technology substitution.	Further adopt cost reflectiveness in all energy pricing. Further adopt a decisive initiative to measure and digitise energy consumption while developing measures to incentivise consumer awareness. Create incentive mechanisms for retrofit and technology substitution.
Climate impacts on energy production (renewable and non-renewable)	Invest in power system flexibility (e.g. transforming coal-fired plants in China to enhance flexibility for the whole electricity system). Enhance sector coupling.	Invest in power system flexibility. Enhance sector coupling Invest in adequate reserves of climate-resilient firm capacity. Invest in more flexible and market-integrated transmission including

Risk	Mitigation measures China	Mitigation measures EU
	Invest in adequate reserves of climate-resilient firm capacity. Invest in more flexible and market-integrated inter-provincial transmission. Invest in both short-term and seasonal energy storage technologies. Incentivising demand response.	new interconnectors between Member States. Incentivise demand response.
Uncoordinated technology transition	Develop a phase-in and phase-out plan focusing on specific metrics. Prolong the use of existing energy infrastructure. Model the mid-transition and evaluate intermediate scenarios. Synchronise scaling up green fuels and technologies with scaling down fossil infrastructure.	Develop a phase-in and phase-out plan focusing on specific metrics. Prolong the use of existing energy infrastructure. Model the mid-transition and evaluate intermediate scenarios. Synchronise scaling up green fuels and technologies with scaling down fossil infrastructure.
Insufficient transmission system integration	Integrate the transmission system into the market mechanism, for example through implicit capacity auction in the market coupling mechanism. Integrated generation-transmission planning. Adopt socialised cost recovery mechanism More flexible inter-provincial transmission, which can adapt to the seasonal characteristics of resources in different regions. Accelerate the development of energy storage. Expand cross-regional infrastructure to transmit renewable power, pursuing transmission rescheduling, netting supply-demand imbalances and expanding resource-sharing areas.	Build new infrastructure/expand existing transmission where profitable (benefits >costs). Adopt socialised cost recovery mechanism in countries where this is not applied. Adopt CBCA (cross border cost allocation) as a cost sharing method. Better utilise existing capacity (e.g. dynamic line rating) Integrated generation-transmission planning. Accelerate the development of energy storage.

4. Quantitative climate impacts on energy production (WP2)

This chapter describes the assumptions and results in work package 2 (WP2) of the project. In this chapter, the risks of a power system being dependent on future large-scale variable renewables are quantitatively assessed. The risks are associated with increased dependency on VRE, which fluctuate with climate and weather patterns, e.g. wind and solar power.

The starting point for this study is the EU in 2050 and China in 2060 - we assume that, in accordance with net zero targets, both electricity systems are fully decarbonised, and a correspondingly high proportion of electricity capacity is covered by VRE resources.

The assessment is done by comparative analysis of the power system adequacy contribution (or load carrying capacity) of RE resources deployed in Europe vis-à-vis China. Essentially the analysis is carried out by comparing the degree to which VRE-resources contribute towards maintaining generation adequacy, relative to projected demands and in the context of changing weather.

Weather vs. Climate

'Weather' refers to the minute-to-minute, hour-to-hour, and day-to-day changes of the atmosphere, while '*climate'* is the weather in a specific area over a long period of time. The European Space Agency defines it as 30 years or more (ESA, n.d.).

This study is based on 20 years of weather data, assessed on different time scales, ranging from hourly to year-to-year. While we evaluate the impact of weather patterns on the production of electricity with VRE sources, our data and assessment are too limited to provide an analysis of climate results.

4.1 Model and scope of the study

The model is using a statistical time series model with a simplified transmission and energy dispatch:

- Spatial scope: EU Member States and Chinese provinces.
- Temporal scope: 20 years of weather reanalysis data (2000-2019) from MERRA-2.[9]

This study considers energy security in mainland China and the EU in separate scenarios. Each scenario is analysed from two levels of spatial scopes.

Level 1: Regional system (EU Member States/Chinese provinces)

Results for the individual EU countries/Chinese provinces are calculated considering only the local production and consumption of energy within each region (hereafter, region=country/province) with no transmission to the neighbouring areas. Transmission

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[9] Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) is an open-source data set provided by NASA. More information can be found here: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/

within the regions has no bottlenecks. Regions in the EU scenarios are equivalent with EU Member States, except for Denmark and Sweden, which are split into multiple regions according to the market bidding zones. Chinese regions correspond to the provinces in mainland China.

Level 2: Total power system (EU/mainland China)

In the total power system, the power per timestep is summed across all countries in the EU and across all provinces in China, respectively. It is assumed that there are no bottlenecks in transmission between European countries or between Chinese provinces. Also, the transmission within EU countries and within Chinese provinces is assumed to have no bottlenecks.

Temporal scope

This study distinguishes between weather years and scenario years. A *weather year* refers to historical years in which the weather had certain characteristics. A weather year can for instance be characterised by low wind or high solar production in comparison to an average weather year. Having multiple decades of weather data can shine light on extreme phenomena that may not occur in an average year.

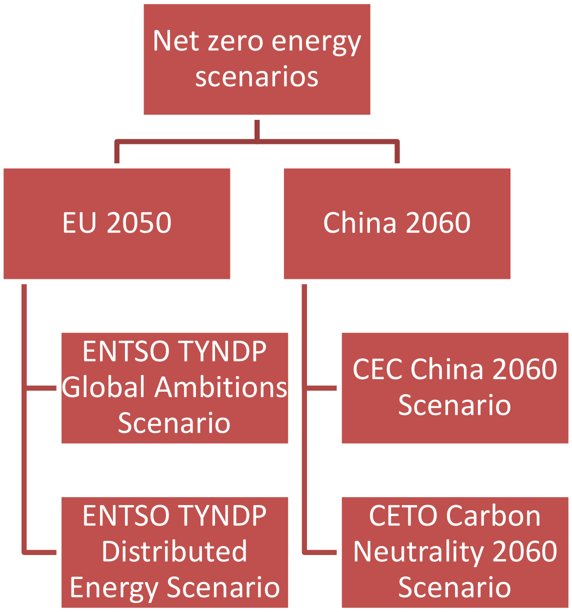
This study is limited to weather variations experienced in historical years, and therefore we do not attempt to estimate the effects of future climate changes. However, the past weather can still give an indication of what weather extremes are possible. The study is based on 20 years of weather data, and we consider different weather years from 2000-2019. This defines the wind and solar profiles, but without any assumptions about the installed capacity.

A *scenario year* refers to a future year with assumed generation capacities and annual electricity demands. In this study, we consider 2050 in EU and 2060 in China to represent scenarios where the respective countries are intended to be fully decarbonised.

Scenarios

According to the policy targets, a scenario is considered in which the EU reached net zero emissions by 2050 and China by 2060. Specific demand projections and wind/solar build-out scenarios for the EU and China are investigated.

Figure 4.1: Overview of net-zero scenarios used in this study



The following four scenarios are analysed in the study (see Figure 4.1 and Table 4.1). In the table the key data of the four considered scenarios are described: two scenarios for 2060 for China and two scenarios for EU for 2050. The table gives key numbers for installed capacities of onshore and offshore wind, solar PV, annual demand and annual (average) VRE coverage.

Table 4.1: Overview of Wind and Solar PV Capacity in the Different Scenarios (China 2060; EU 2050)

Scenario	Onshore wind (GW)	Offshore wind (GW)	Solar PV (GW)	Annual demand (TWh)	Annual VRE coverage (%)
CEC China	1 885	159	3 278	15 701	72%
CETO China, CNS2	3 486	703	4 804	14 104	154%
TYNDP Global Ambition EU	546	342	1 048	3 864	126%
TYNDP Distributed Energy EU	845	298	1 584	4 344	144%

The annual VRE coverage in Table 4.1 is calculated as the mean annual VRE generation for the sum of all regions divided by the annual demand for the sum of all regions. The mean values are calculated based on all meteorological weather years (2000-19). The annual demand figures in Table 4.1 do not include demand for e.g., P2X. This mean that the VRE coverage shown can be higher than 100% without necessarily having curtailment.

The scenario data for China is provided from CEC[10] and from the CETO project. Likewise, the scenario data from EU corresponds to ENTSO-E's TYNDP scenarios: Global Ambition and Distributed Energy, respectively (ENTSOG & ENTSO-E, 2021).

EU scenario data

The 2050 EU scenario data is based on the *Global Ambition (GA) Scenario* and the *Distributed Energy Scenario* of the Ten Year Network Development Plan (TYNDP), which is jointly developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Network of Transmission System Operators for Gas (ENTSOG). Both scenarios aim to reach at least 55 % reduction of greenhouse gas emissions in 2030 and the EU climate neutrality target in 2050. While the Global Ambition Scenario aims to reach these targets with a focus on large-scale technologies, such as offshore wind and large storage, the Distributed Energy Scenario focuses on decentralised technologies, such as solar PV, batteries, and smart charging. While the Distributed Energy Scenario considers only a minimum share of CCS and nuclear energy, the Global Ambition Scenario incorporates CCS and nuclear at a larger scale to reach the net-zero target (ENTSOG & ENTSO-E, 2022).

The scenario data used in this study is based on the climate year 2009 (ENTSO-E, 2023b). For Greece and Italy, data from all bidding zones were aggregated to country level, while data for Denmark and Sweden were analysed according to the zones defined in the scenario, which are equivalent to the bidding zones in the European electricity market.

China scenario data

CEC China 2060 scenario data

China solar PV and onshore wind capacity data of the CEC China 2060 scenario is based on the 'China Electric Power Statistical Yearbook 2022' and 'The 2023 Annual Report of Power Industry development in China', published by CEC (CEC, 2022, 2023). Annual growth of the VRE capacity is assumed to be 40 GW wind and 70 GW solar in the period of 2022-2030, 40 GW wind and 75 GW solar in the time between 2031-2045 and 40 GW wind and 80 GW solar in 2046-2060. Based on the VRE shares in each province in 2022, the VRE shares of central and eastern provinces are considered with slight increases of 3.5% for solar and 2.6% for wind, and the shares of western and northern provinces are reduced accordingly.

Offshore wind capacity data in the coastal provinces is based on the 'China Wind Power Industry Map 2021', published by the Chinese Wind Energy Association (C. Chen, 2022; CWEA, 2022), as well as the GEIDCO (2021) study report 'China's 2030 Power Development Plan and 2060 Outlook' with a suggestion of 159 GW offshore wind. Based on the shares of offshore wind in the coastal provinces, the 159 GW are assumed to be similarly distributed as in 2021.

China's demand data forecast is based on an academic paper published on the carbon neutrality path for China's power industry (Shu et al., 2021), which projects 15 700 TWh annual electricity demand in 2060. Based on the demand shares of each province in 2022, the shares of the western and northern provinces show a slight increase of 2.93% and the shares of the central and eastern provinces are reduced accordingly.

CETO scenario data

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[10] The CEC data are explained in 'Introduction of Scenarios and Data Collection', CEC. The note is included in Annex.

The solar PV and wind capacity data in the CETO carbon neutral scenario are based on China carbon neutral scenario (CNS2) of the China Energy Transformation Outlook (CETO), which is prepared annually by the Energy Research Institute of the Chinese Academy of Macroeconomic Research with partners (ERI, 2022). The carbon neutral scenarios of the CETO report present a way to meet the climate targets to peak CO_2 emissions before 2030 and reach carbon neutrality before 2060.

Time series modelling

Energy security risks from VRE are linked to the variability of VRE generation. Therefore, it is important to use data with a high time resolution. This study considers generation and consumption of energy based on profiles with an hourly resolution.

VRE generation

Weather reanalysis is a methodology which utilises satellite observations and historical weather forecasts and observations as inputs to global weather models. This enables access to output weather data at hourly resolution for any location on Earth and a large selection of historical weather years. It should be noted that reanalysis data is not a precise representation of past weather, and the accuracy depends on how well particular areas have been calibrated. Nonetheless, it represents the most complete and detailed picture of past weather available.

The study is based on the MERRA-2 dataset available from Renewables.ninja (2023). Wind speeds are sampled at a height of 100 m. Solar irradiance is collected assuming south-facing panels with a tilt angle of 35 degrees between the panel and the ground.

For the study, specific locations are selected to represent the regions. Wind and solar data are sampled from the same location per region. As a simplification, weather data is sampled from one onshore location per region and one offshore location per coastal region. This has the consequence of making the weather analysis rather sensitive to particular locations. The physical deployment of wind and solar would use a wide range of locations inside any given region. This would most likely make the variability smoother than what is assumed in this study, since extreme weather tends to average over large geographical distances.

Electricity demand

The consumption of electricity is also linked to weather conditions, especially if there is a high degree of electrification in the heating sector. The study is limited to considering demand profiles originating from a single weather year. Thus, when analysing different weather years, the demand profile is simply repeated. For demand in China, regional profiles from Ea's EDO model are used representing China in the CETO project.

For the scenarios in the EU, we use demand profiles from ENTSO-E TYNDP (weather year 2009) (ENTSOG & ENTSO-E, 2021). The profiles from the TYNDP are based on specific historical weather years, assuming demand dynamics of a 2050 system where society is highly electrified. Such detailed demand profile modelling is not available for China. However, in all scenarios the profiles are scaled to match the annual consumption of a future scenario year. The peak demands reported in this study are based on these profiles along with the annual demand and should therefore be considered as estimates.

Residual load is a measure of the difference between demand and VRE generation. It can be a positive value when demand exceeds VRE generation (energy deficit), or it can be a negative value when VRE generation exceeds demand (energy surplus). It is a key measure that will be reported throughout this study.

Weather to energy conversion

In order to see how changes in weather impact VRE generation, the sampled weather variables must be converted into energy production. For solar, the solar irradiance received on a given point of Earth is already a measure of power and is available from the weather model in a normalised range between 0 and 1.

For wind, the power output depends on the specific turbine model that is manufactured to operate in different wind regimes. For instance, low wind regions can benefit from turbines with larger rotors that produce more power at low wind speeds. However, to better compare across regions and continents, we use a reference onshore wind turbine (NREL, 2020b) and reference offshore turbine (NREL, 2020a). Wind speeds are converted to power using the power curves of these turbines (see Table 4.2).

Table 4.2: Technical Data on Reference Wind Turbines

		Onshore	Offshore
Name of turbine		IEA 3.4 MW Reference	IEA 10 MW Reference
Rated Power	kW	3370	10000
Rated Wind Speed	m/s	9.8	11
Cut-in Wind Speed	m/s	4	4
Cut-out Wind Speed	m/s	25	25
Rotor Diameter	m	130	198

Data Source: NREL (2020b, 2020a).

Note: *The study considers an idealised energy system with no losses. In reality, the conversion and transportation of energy would lead to different kinds of losses. Furthermore, wake losses from wind farms are not accounted for. The consequence of this limitation is that an overestimation of VRE production and an underestimation of residual load will occur in this study compared to an actual physical power system.*

Normalisation

The scale of generation and consumption of energy varies greatly across the geographical areas investigated in this study. In order to compare results between EU and China, the data is normalised. Wind and solar generation are normalised to their respective installed capacities within the area in question. Generation is therefore shown on a scale between 0 and 1, where 1 indicates the full load. Electricity demand and residual load are both normalised to the peak demand.

4.2 Analysis methodology

The following paragraphs explain a few key concepts that are important for the analysis and an understanding of the results.

Duration curves

A *duration curve* is a measure that shows how long a certain level of power is maintained in a power system. It gives an overview of the demand, wind and solar resources and VRE adequacy. The following variables are presented:

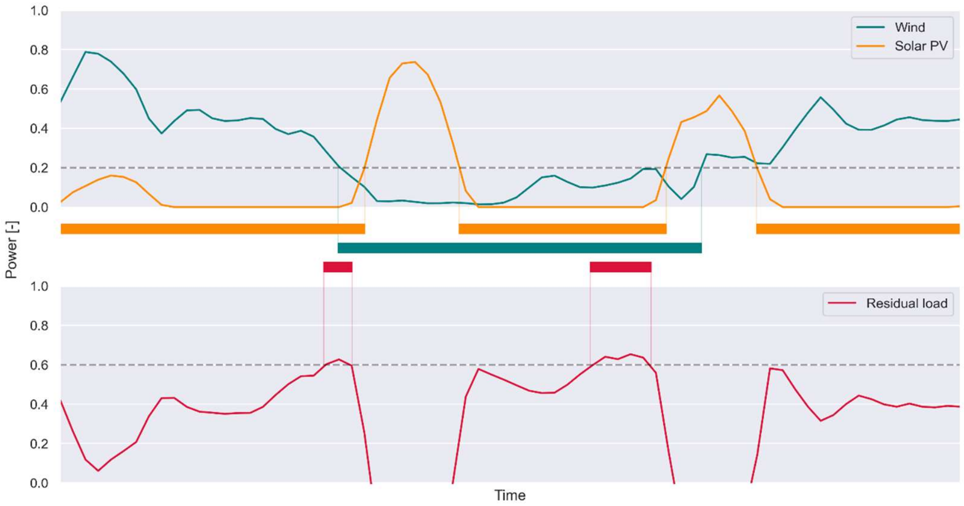
- Wind generation.
- Solar generation.
- Demand.
- Residual load.

In this study, duration curves are based on all the time steps, utilising the full 20 years (2000-19) of weather data. Each variable is ranked independently from highest to lowest power.

Energy droughts

It is not only the magnitude of an energy security risk that determines its severity. The term *energy drought* denotes a situation where the power system is at risk due to inadequacy for a prolonged period of time. The definitions in this study are inspired by Raynaud et al. (2018). An energy drought can be due to wind and solar generation being continuously at a low level. But it can also be due to an imbalance between production and demand resulting in a high residual load for a long period of time**. In this study, an energy drought event is defined as a period of time where VRE generation is below a certain threshold or residual load is above a certain threshold in all time steps.** Crossing the threshold therefore means either the start or termination of an energy drought event. This is illustrated in Figure 4.2.

Figure 4.2: Illustration of energy droughts



Note: *Example of energy droughts. The dashed horizontal lines mark the thresholds. The durations of the drought events are illustrated with horizontal bars in the middle of the graph. Wind and solar production are normalised to their capacities and residual load is normalised to peak demand.*

In this study, energy droughts are categorised according to the following thresholds:

- Generation is below 20% of capacity.
- Generation is below 30% of capacity.
- Generation is below 40% of capacity.
- Residual load is above 60% of peak demand.
- Residual load is above 50% of peak demand.
- Residual load is above 40% of peak demand.

To quantify the energy droughts, the first step is to categorise all time steps of all the weather years according to the above mentioned categories. The next step is to calculate the duration of each single period of time that falls into the categories. Each such period is defined as an energy drought event, thus characterised by a magnitude and duration (for instance, wind production being below 20% of capacity for four days).

Afterwards, all energy drought events are ranked according to their duration and a probability is calculated. The probability of an energy drought event denotes the likelihood of seeing an event with a particular magnitude for a certain duration. Thus, the probability is defined as the number of time steps that qualify as a particular event divided by the entire number of time steps in all 20 weather years.

4.3 Flexibility needs

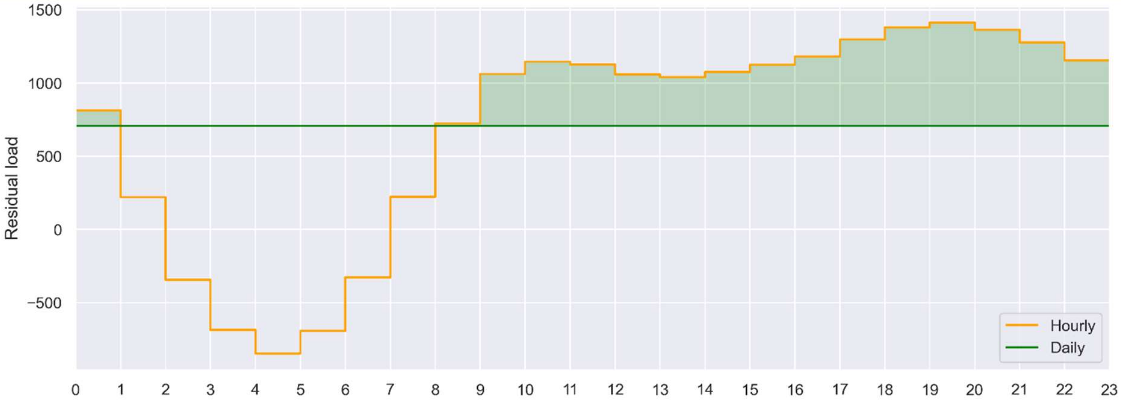
When the residual load is positive (in other words, when demand exceeds VRE generation), other types of energy than wind and solar must keep the power system in balance. If the residual load is completely flat over time, the remaining energy could be covered by baseload capacity. However, the coinciding patterns in demand and variability from wind and solar means that residual load is fluctuating. Rather than a constant output to compensate, the system will likely need flexibility to ramp up and down to stay in balance. This flexibility can come from a wide variety of sources, including grid-scale batteries, demand response, pumped hydro etc. The selection of flexibility measures will often depend on the time scale at which flexibility is needed. This study considers flexibility needs on three different time scales and is based on a methodology commissioned by the European Commission (2017).

In this study, *flexibility needs* is a metric defined as the amount of energy that must be 'shifted around' to balance the residual load within the time scale of a day, a week, and a year, respectively. Regardless of the time scale, the energy amount is aggregated to an annual sum. This enables comparison between the flexibility needs at different time scales. Note that this annual sum cannot be used to estimate e.g., storage volume, since multiple storage cycles would take place over the course of a year. The calculation is carried out for each weather year separately and the distribution of annual sums is reported. The annual sums of flexibility needs can then be presented as percentage values compared to e.g., the annual demand.

Daily flexibility needs

Daily flexibility needs are the positive difference between hourly residual load and daily mean of residual load. It shows the amount of energy that must be 'shifted around' over the time of a day. This is illustrated in Figure 4.3.

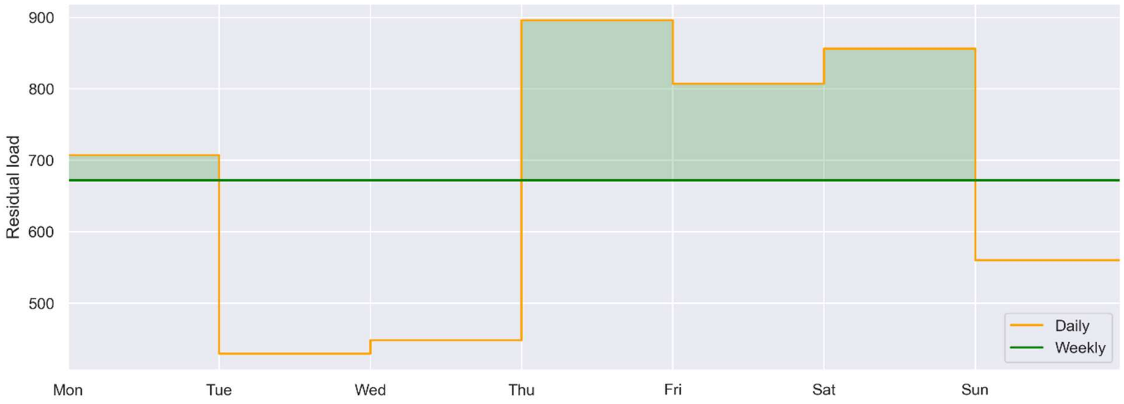
Figure 4.3: Daily flexibility needs (the green area is the amount of energy that must be 'shifted around' over the day)



Weekly flexibility needs

*We*ekly flexibility needs refers to the positive difference between daily mean of residual load and weekly mean of residual load (see Figure 4.4). The Figure shows the amount of energy that must be 'shifted around' over the period of a week.

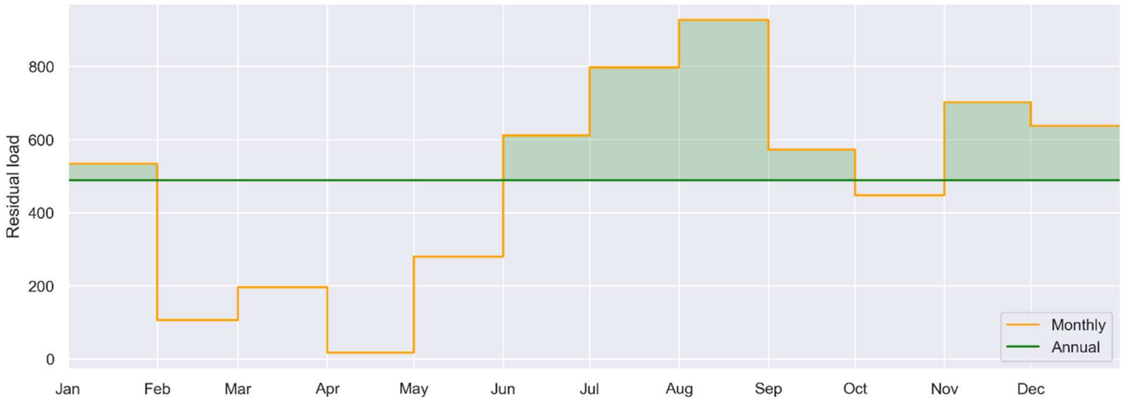
Figure 4.4: Weekly flexibility needs (the green area is the amount of energy that must be 'shifted around' over the week)



Annual flexibility needs

Annual flexibility needs measures the positive difference between monthly mean of residual load and annual mean of residual load (see Figure 4.5). The Figure shows the amount of energy that must be 'shifted around' over the time of a year.

Figure 4.5: Yearly flexibility needs (the green area is the amount of energy that must be 'shifted around' over the year)



4.4 Results

In the following, the results of the comparative analysis of the power system adequacy contribution (or load-carrying capacity) of VRE resources deployed in Europe vis-à-vis China are presented. We focus here on the presentation of the results of the CEC China 2060 scenario and the ENTSO TYNDP Global Ambition EU 2050 scenario. Results of the

CETO China 2060 scenario and the ENTSO TYNDP Distributed Energy EU 2050 scenario are available in a separate Annex. Regional results (EU Member States and provinces of mainland China) are also only presented here to a limited extent and can be viewed in the separate Annex.

Results of the following key measures are presented in this section:

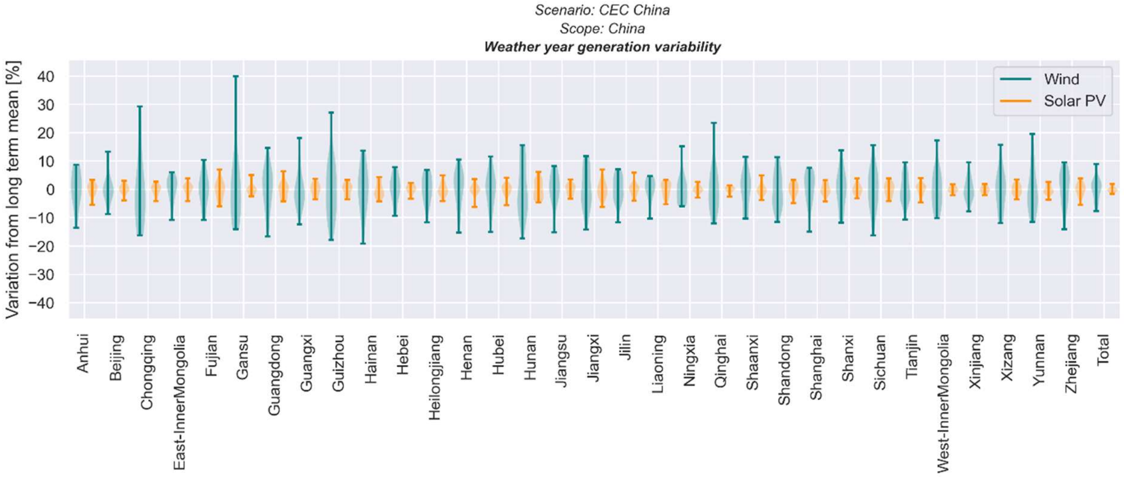
- VRE generation variability.
- Duration curves.
- Energy droughts.
- Flexibility needs.

VRE generation variability

Generation variability is the extent to which generation from a power source fluctuates. The inter-annual variability of wind and solar generation across the 20 weather years analysed is shown in Figure 4.6 and Figure 4.7. for China and the EU, respectively. For China the CEC scenario and for the EU the Global Ambition Scenario form the basis of the analysis.

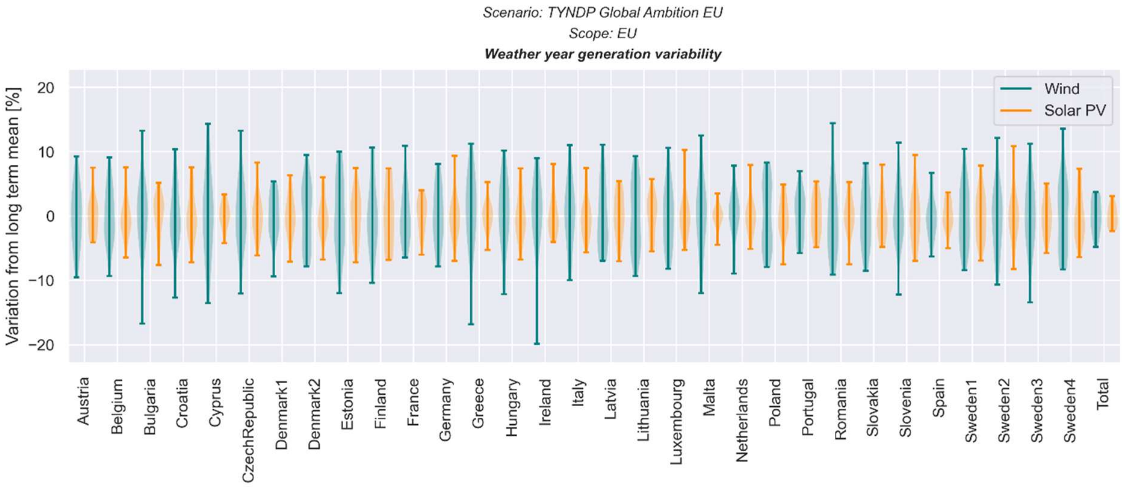
Wind is generally more variable than solar PV at an annual time scale. The variation of the 'total' (columns to the far right in figures showing the generation variability for whole of mainland China/whole EU) is smaller than most of the regional variability, which shows that deviations as expected tend to smoothen when considering larger geographies.

Figure 4.6: CEC China scenario. Variability in annual wind and solar generation across weather years



Note: The whiskers indicate the range of variability and the shape between the minimum and maximum indicates the distribution of annual energy.

Figure 4.7: EU Global Ambition Scenario. Variability in annual wind and solar generation across weather years



Note: The whiskers indicate the range of variability and the shape between the minimum and maximum indicates the distribution of annual energy

Duration curves

How long a certain level of power is maintained in a power system is shown in duration curves. Figure 4.8 and Figure 4.9 show the duration curves as results for the whole of China and the EU in the CEC scenario and the Global Ambitions Scenario. The curves are normalised with respect to installed wind and solar capacities, respectively. Residual load is normalised with respect to peak demand[11]. All 20 years of data are considered in the Figures.

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[11] Peak demand is calculated based on yearly demand (CEC) and demand profiles from the CETO project.

Figure 4.8: Duration curves - CEC China scenario

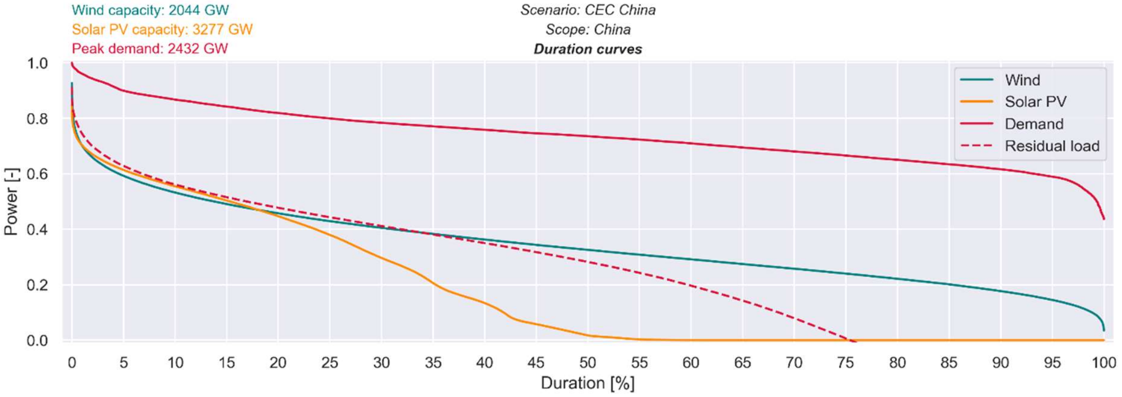
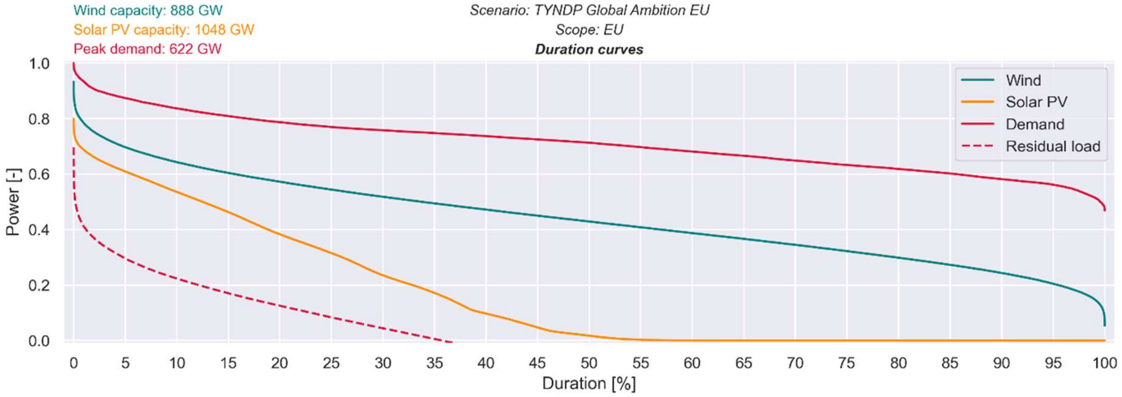


Figure 4.9: Duration curves - EU Global Ambition Scenario



In China, VRE will cover the entire demand around 25% of the time while the corresponding figure for EU is about 65%. However, in principle, the comparison between the EU and China is difficult at this point because the scenarios are structured very differently. The main explanation is that the annual VRE generation coverage is much higher in the EU scenario (126%) than in the China scenario (72%) (see Table 4.1: Overview of Wind and Solar PV Capacity in the Different Scenarios (China 2060; EU 2050).

For hours with high residual peak, capacity mechanisms could support energy security. It is observed that the residual load curves in both China and EU are very steep towards their maximum. This is the case for the other scenarios as well. Even regions with very high VRE penetration (such as Denmark, Hebei or Shanxi) still have high residual peaks in a small number of time steps (see Figure 4.10, Figure 4.11 and Figure 4.12). Thus, continued build-out of VRE is unlikely to provide energy security in those hours which indicates a need for high backup capacity to ensure power adequacy at all times.

This is likely to be expensive as the spot market is not expected to provide incentives to build backup power (e.g. natural gas turbines), due to the low foreseen number of operational hours. The solution could be a capacity mechanism, such as a separate market for remunerating capacity being kept ready for covering the residual load deficit. In this market, generators, electrical storage or demand reductions could participate. Import of additional supplies via interconnectors could also be considered.

Figure 4.10: Duration curves. Denmark 1 - Global Ambition Scenario

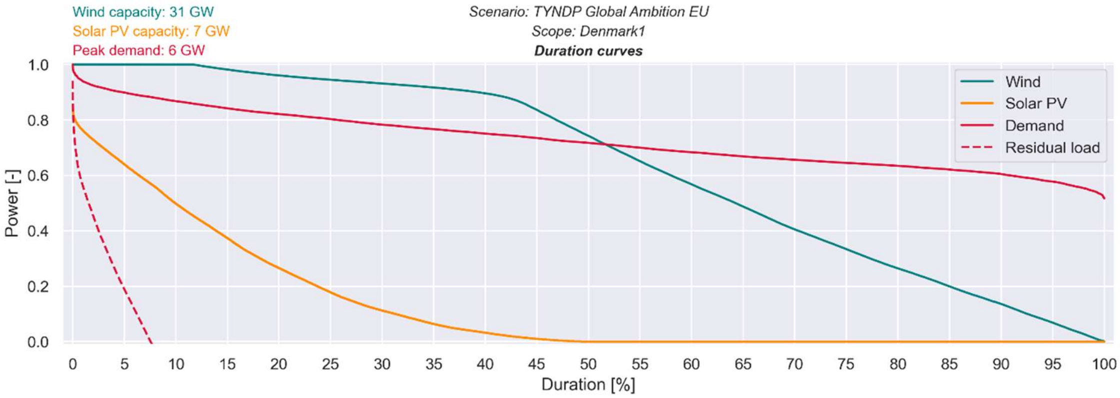


Figure 4.11: Duration curves. Hebei - CEC China scenario

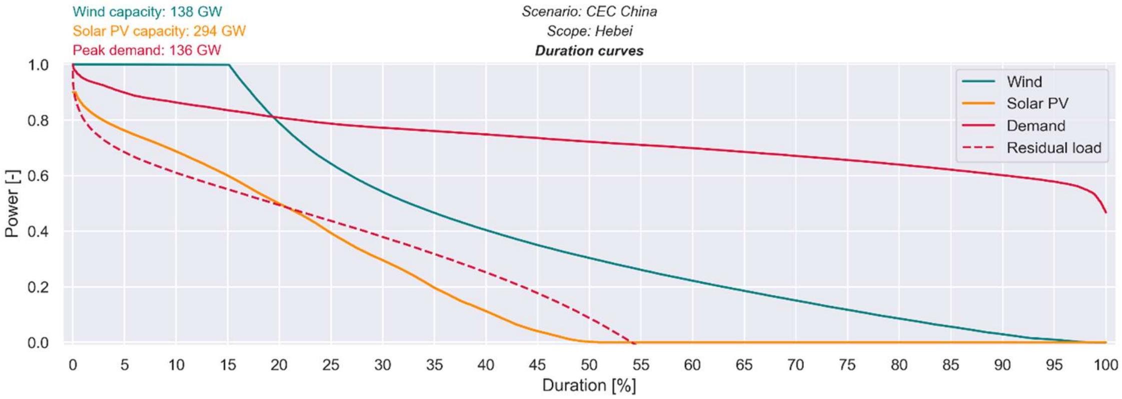
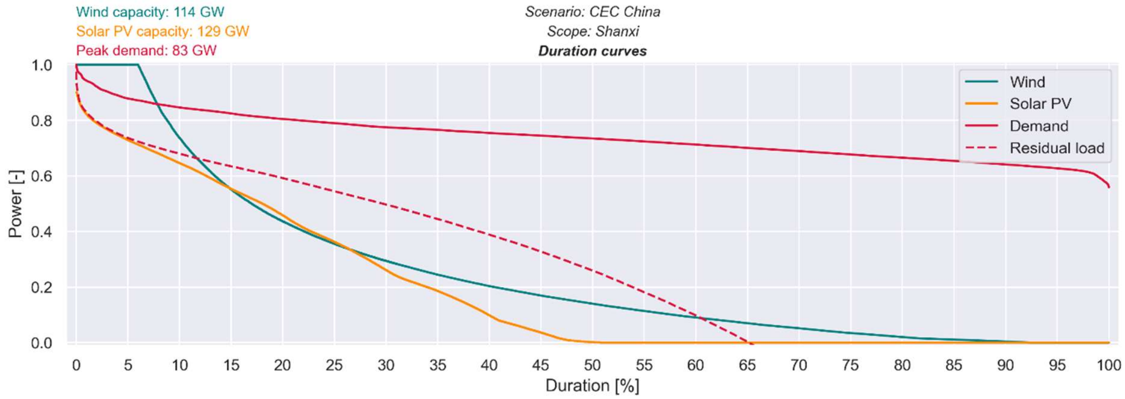


Figure 4.12: Duration curves. Shanxi - CEC China scenario



Energy droughts

Times in all time steps during which VRE generation is below a certain threshold, or residual load is above a certain threshold are so-called *energy droughts*. Energy droughts therefore show the risk that energy demand cannot be covered by VRE generation. In the following we will look into results for energy droughts.

Three different thresholds are shown on the graphs for droughts representing levels of severity of energy droughts in terms of magnitude. The green graphs show the mildest events in terms of magnitude. They tend to happen more often and can also last longer. The yellow and red graphs are events where VRE power is less adequate, but these events are generally less likely to happen and less long-lasting (see Figure 4.13 – Figure 4.17).

The results for energy droughts are shown for mainland China as a whole and the EU as a whole without transmission bottlenecks between Chinese provinces and EU countries. Under this assumption, electricity can flow unconstrained from any generation site to any demand site. An exception is only made for Denmark and Sweden, which are divided into several bidding areas according to the Nord Pool electricity market[12]. However, the assumption of no bottlenecks holds between the different bidding areas as well.

Energy drought events with a low adequacy for short periods of time (red graphs) and events with moderate adequacy for longer periods of time (yellow and green graphs) can both pose energy security risks.

Note on energy drought figures: *The probability is cumulative and therefore denotes a risk of event of* *<u>at least</u>* *a given duration. The maximum duration of energy droughts is given in text in the figures in cases where it was not practical to show the full set of data points.*

Wind energy droughts are of lower duration in the EU than in China. This is because the wind climate is in general better in the EU than in China (higher average capacity factor) (see wind duration curves in Figure 4.8 and Figure 4.9). Moreover, in the

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[12] For the different Nord Pool bidding areas see: https://www.nordpoolgroup.com/en/the-power-market/Bidding-areas/

EU the share of offshore wind capacity is higher and tends to be in areas with higher wind availability. In China, wind energy droughts exist in the realm of days to weeks: a maximum of five days for severe events with wind power generation below 20% of capacity and up to 58 days with generation below 40% of capacity (see Figure 4.13). The corresponding numbers for the EU are four days and 17 days, respectively (see Figure 4.14).

Figure 4.13: Wind energy drought - CEC China scenario

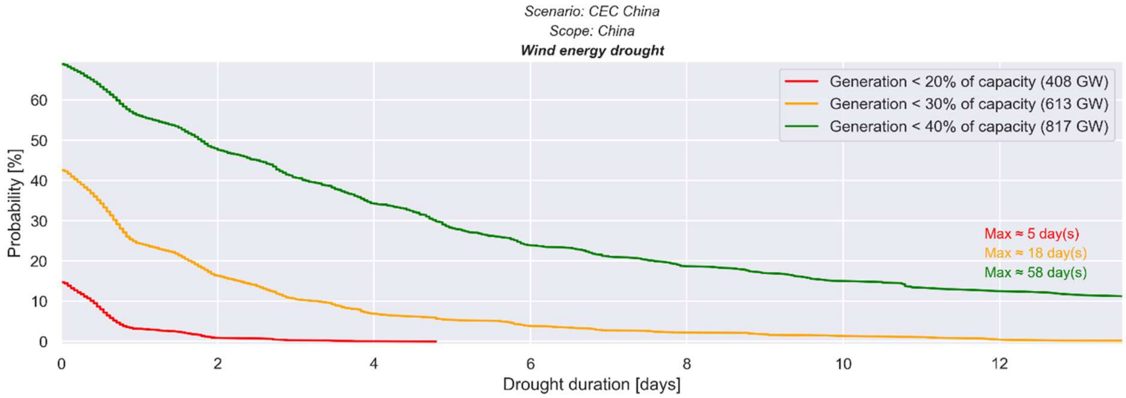
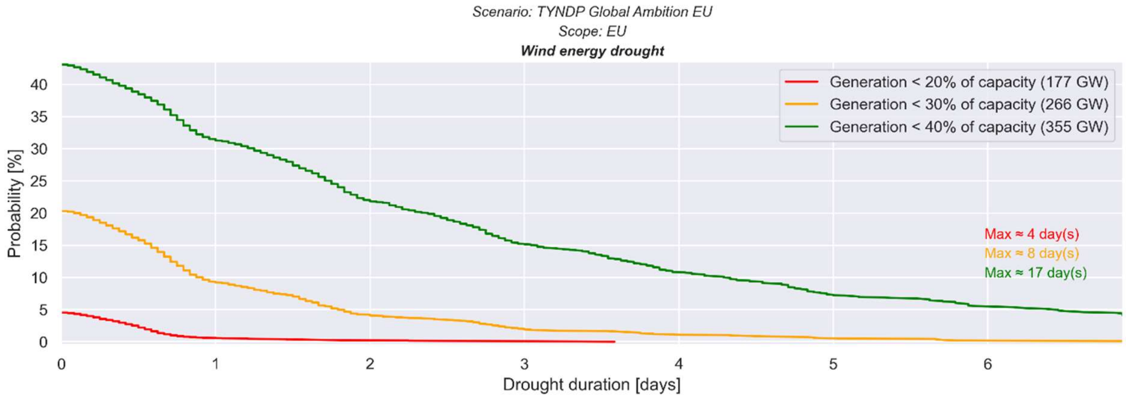


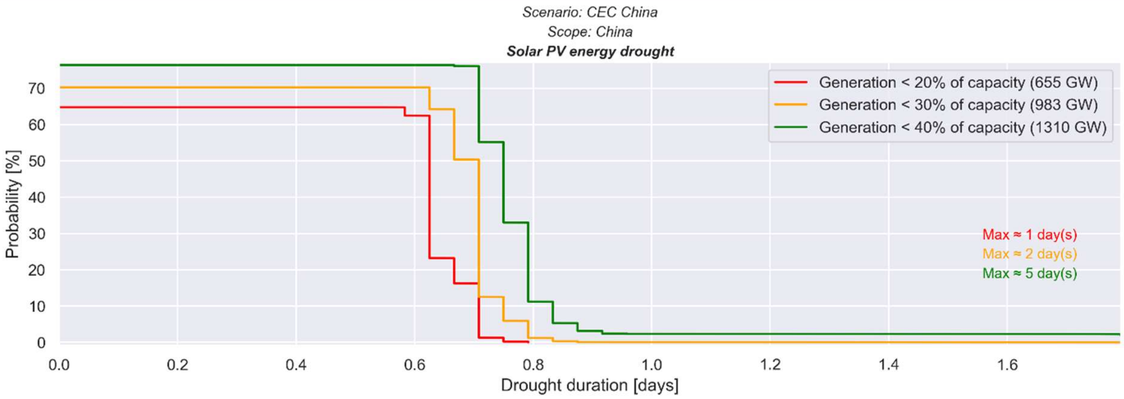
Figure 4.14: Wind energy drought - EU Global Ambition Scenario



Solar PV duration curves are very similar for China and the EU (compare Figure 4.8 and Figure 4.9). However, the duration of the droughts is very different (compare Figure 4.15 and Figure 4.16). It is seen that droughts in all categories are of lower duration in China than in Europe.

China: Solar energy droughts can be split into two phenomena. Short droughts of less than a day are very likely to occur and can be explained by the daily pattern of sunrise and sunset. Around 70% of all time steps show these short energy droughts corresponding to night-time hours. Events lasting longer than a day due to seasonality and overcast skies are quite unlikely for the entire country at the same

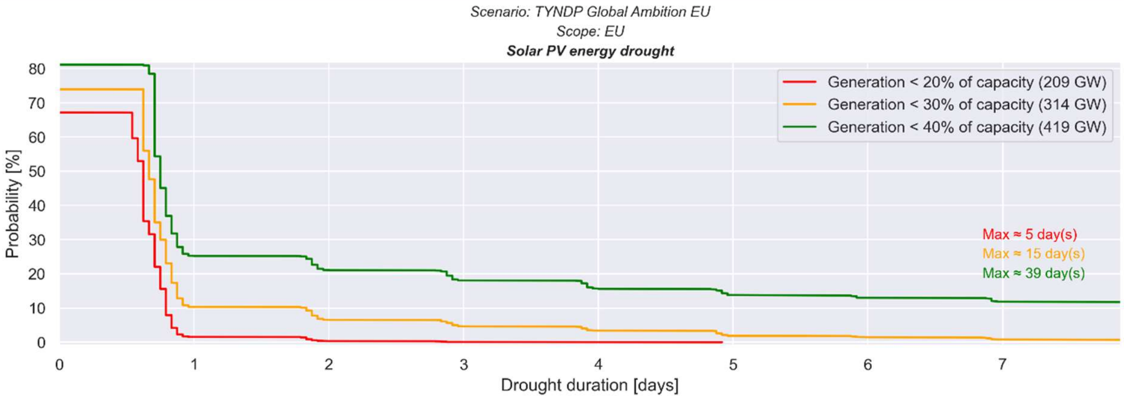
Figure 4.15: Solar PV drought - China CEC scenario



EU: Solar energy droughts in the EU show the same daily pattern as in China with a high probability of short-term solar droughts. However, long-term solar droughts generally last longer in the EU than in China.

The EU has on average a larger seasonal impact over the year. For example, the EU has long nights (no solar) during winter due to its higher latitude. However, most of the solar droughts tend to be short-term, e.g., 90% of the more severe events with less than 30% PV capacity have a duration of less than one day.

Figure 4.16: Solar PV drought - EU Global Ambition Scenario



The durations of residual load droughts are generally very short (most events last less than a day) in both China and the EU. However, the probability of events is much lower in EU than in China. The main explanation is that the annual VRE generation coverage is much higher in the EU scenario (126%) than in the China scenario (72%) (see Table 4.1).

Residual load energy droughts are shown in Figure 4.17 and Figure 4.18 for China and the EU, respectively.

Figure 4.17: Residual load energy drought - China CEC scenario

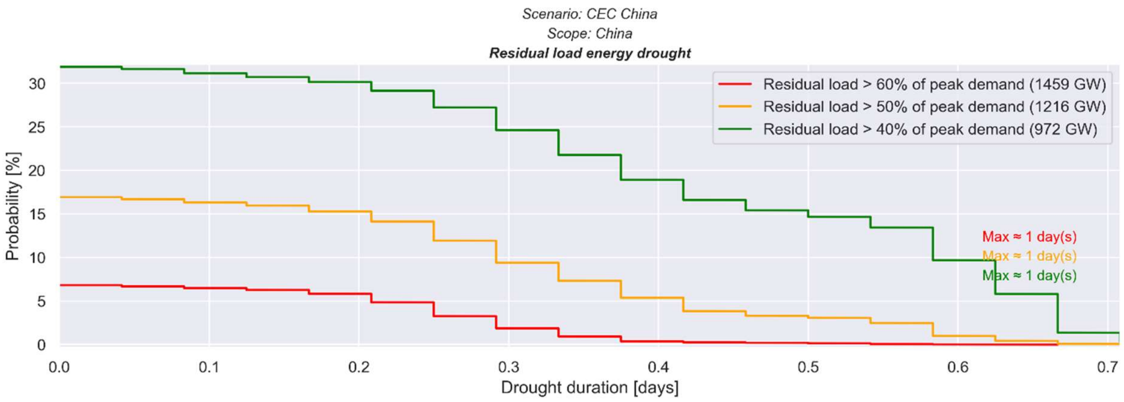
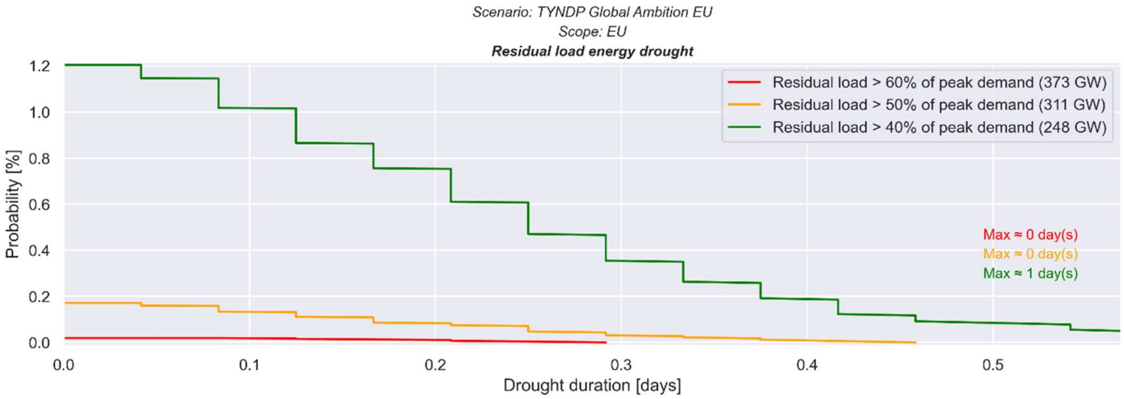


Figure 4.18: Residual load energy drought - EU Global Ambition Scenario



The power system needs to balance generation and demand, and the more concrete risk of energy droughts is therefore related to whether low generation and high demand coincide for a long period of time.

The need for long-term baseload capacity is limited, but more flexibility resources would be useful to fill VRE generation gaps. Despite wind and solar droughts lasting several days, the daily demand pattern ‘breaks’ the residual load drought into shorter ones. However, the probability indicates that drought events happen quite frequently in China. This demonstrates that flexible sources of energy generation or demand that can ramp up/down quickly would be valuable to the system to fill the frequent gaps left by VRE. The need for a baseload capacity to operate for long coherent time periods with low wind/solar and high demand seems limited.

Again, it should be noted that the results presented here for residual load energy droughts are made at total power system level for both China and EU, assuming no transmission bottlenecks. The results may differ and vary significantly at country or province level.

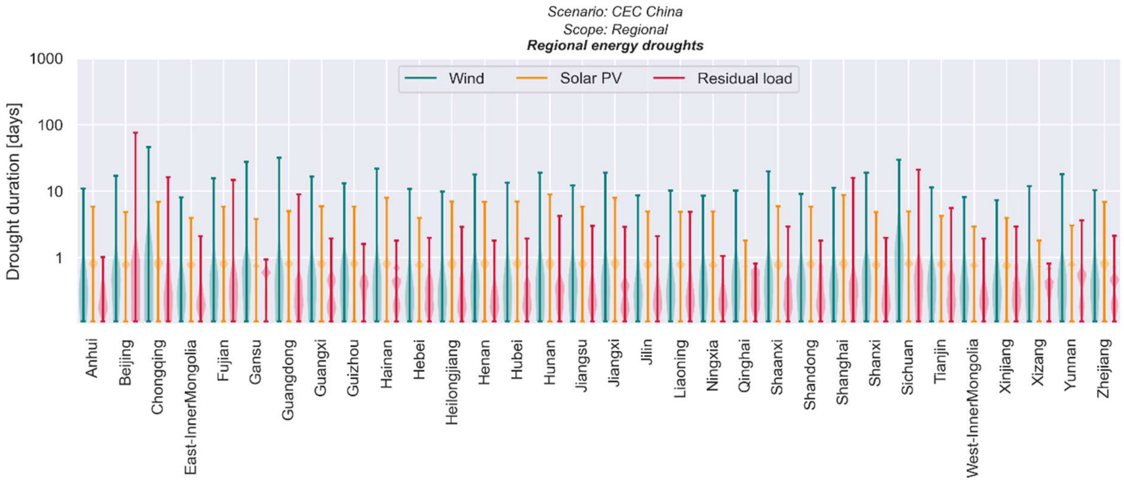
Energy droughts on province and country level

At a regional level (EU Member States and Chinese provinces), energy droughts tend to be longer.

Figure 4.19 and Figure 4.20 show results for energy droughts for individual provinces in China and countries in the EU, respectively. The results show the regional energy droughts without considering possible inter-regional transmission (basically a copperplate assumption within the region, but no exchange between regions). As we can see from the results, regions with a low VRE coverage like Slovakia in the EU and Beijing in China tend to have longer residual load droughts. This highlights the importance of inter-regional transmission capacity/interconnectors and electricity markets.

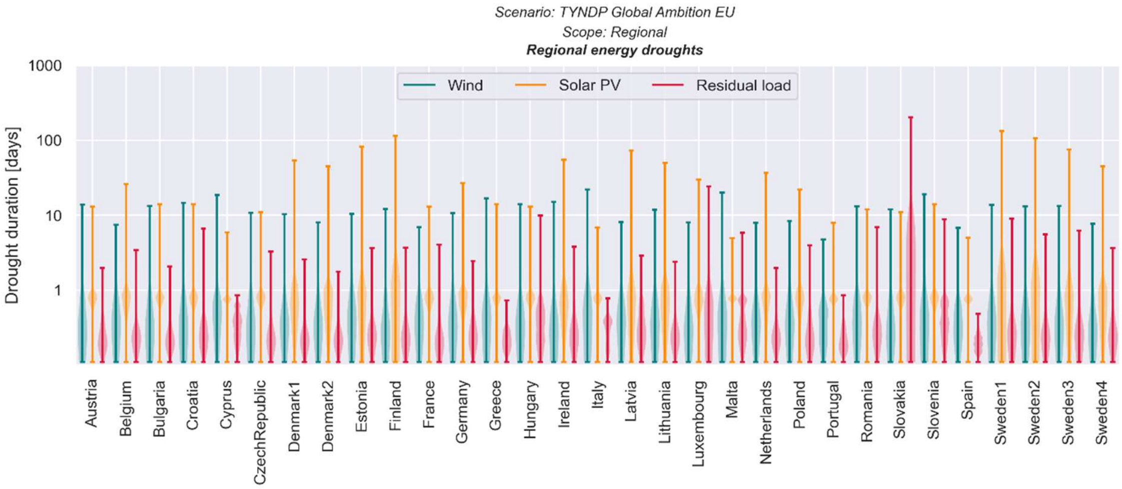
See also Table 4.3 and Table 4.4. In all illustrations the thresholds for energy droughts are: residual load >50% of peak demand and wind/solar generation <30% of capacity.

Figure 4.19: Regional results of energy drought in China - China CEC scenario.



Note: *Wind and solar energy droughts solely depend on wind and solar weather patterns, while residual load droughts depend on installed capacities of wind and solar, weather patterns and demand. Residual load > 50 % of peak demand and wind/solar generation < 30 % of capacity. Note that the y-axis is logarithmic*

Figure 4.20: Regional results of energy drought in the EU - EU TYNDP Global Ambitions Scenario.



Note that the y-axis is logarithmic. Wind and solar energy droughts solely depend on wind and solar weather patterns, while residual load droughts depend on installed capacities of wind and solar, weather patterns and demand. Residual load >50% of peak demand and wind/solar generation <30% of capacity

Table 4.3: Regional Results of Energy Droughts in China - China CEC Scenario. Residual Load >50% of Peak Demand and Wind/Solar Generation <30% of Capacity

	Wind drought (max) days	Solar drought (max) days	Residual load drought (max) days
Anhui	11	6	1
Beijing	17	5	76
Chongqing	46	7	16
East-Inner Mongolia	8	4	2
Fujian	16	6	15
Gansu	28	4	1
Guangdong	32	5	9
Guangxi	17	6	2
Guizhou	13	6	2
Hainan	22	8	2
Hebei	11	4	2
Heilongjiang	10	7	3
Henan	18	7	2
Hubei	13	7	2
Hunan	19	9	4
Jiangsu	12	6	3
Jiangxi	19	8	3
Jilin	9	5	2
Liaoning	10	5	5
Ningxia	8	5	1
Qinghai	10	2	1
Shaanxi	20	6	3
Shandong	9	6	2
Shanghai	11	9	16
Shanxi	19	5	2
Sichuan	30	5	21
Tianjin	11	4	6
West-Inner Mongolia	8	3	2
Xinjiang	7	4	3
Xizang	12	2	1
Yunnan	18	3	4
Zhejiang	10	7	2

Note: For the purpose of this study, we have divided Inner Mongolia into two regions (east Inner Mongolia and west Inner Mongolia) based on the modelling criteria.

Table 4.4: Regional Results for Energy Droughts in the EU - EU Global Ambitions Scenario. Residual Load >50% of Peak Demand and Wind/Solar Generation <30% of Capacity

	Wind drought (max) days	Solar drought (max) days	Residual load drought (max) days
Austria	14	13	2
Belgium	7	26	3
Bulgaria	13	14	2
Croatia	15	14	6
Cyprus	18	6	1
Czech Republic	11	11	3
Denmark1	10	54	2
Denmark2	8	45	2
Estonia	10	82	4
Finland	12	114	4
France	7	13	4
Germany	11	27	2
Greece	17	14	1
Hungary	14	13	10
Ireland	15	55	4
Italy	22	7	1
Latvia	8	73	3
Lithuania	12	50	2
Luxembourg	8	30	24
Malta	20	5	6
Netherlands	8	37	2
Poland	8	22	4
Portugal	5	8	1
Romania	13	12	7
Slovakia	12	11	174
Slovenia	19	14	9
Spain	7	5	0
Sweden1	14	133	9
Sweden2	13	106	5
Sweden3	13	75	6
Sweden4	8	45	4

Note: Wind and solar energy droughts solely depend on wind and solar weather patterns, while residual load droughts depend on installed capacities of wind and solar, weather patterns and demand.

From the data in Table 4.3 and Table 4.4, it follows that there are high regional variations of maximum durations of droughts within both China and the EU. By comparing the tables, it is seen that maximum solar drought are significantly longer in EU countries than in Chinese provinces. This is in conformity with the comparison of China and the EU on total power system level (see Figure 4.15 and Figure 4.16). On average, the EU sees a larger seasonal impact over the year with e.g., long nights (no solar) during winter due to its higher latitude. However, on average for the total power system in the EU most of the solar droughts tend to be short-term, e.g. 90% of the more severe events with less than 30% PV capacity have a duration of less than one day. Northern regions in the EU can experience solar droughts lasting several months (see Table 4.4).

Note: *The long duration residual load droughts in e.g. Beijing, Shanghai, Sichuan, and Slovakia are mainly due to high electricity demand compared to installed VRE capacities. While the model treats each country or province as a separate entity, they are connected to a regional system that supports the balancing of power generation and consumption. For instance, Beijing belongs to the North China regional system and relies on importing electricity from other regions to maintain high power supply reliability. This is an important factor to consider when analysing the impact of VRE on the power system.*

Flexibility needs

Electric supply and demand must be balanced at all times. The amount of energy that needs to be 'shifted around' to balance the residual load within a certain time scale gives the *flexibility needs* of the system. The following figures show the results for daily, weekly, and annual flexibility needs in China and in the EU. (See Figure 4.21 – Figure 4.26).

Note*: Flexibility needs are shown at daily, weekly, and annual time scales. The whiskers indicate the range of variability across weather years and the shape between the minimum and maximum indicates the distribution. The y-axis is a percentage of annual energy demand.*

Figure 4.21 Daily flexibility needs - China CEC scenario

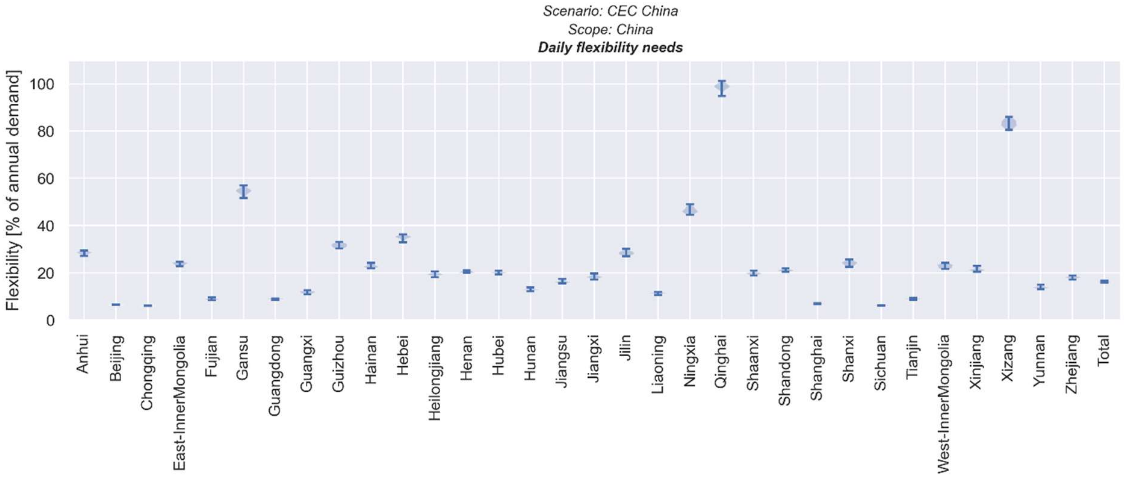


Figure 4.22: Daily flexibility needs - EU Global Ambition Scenario

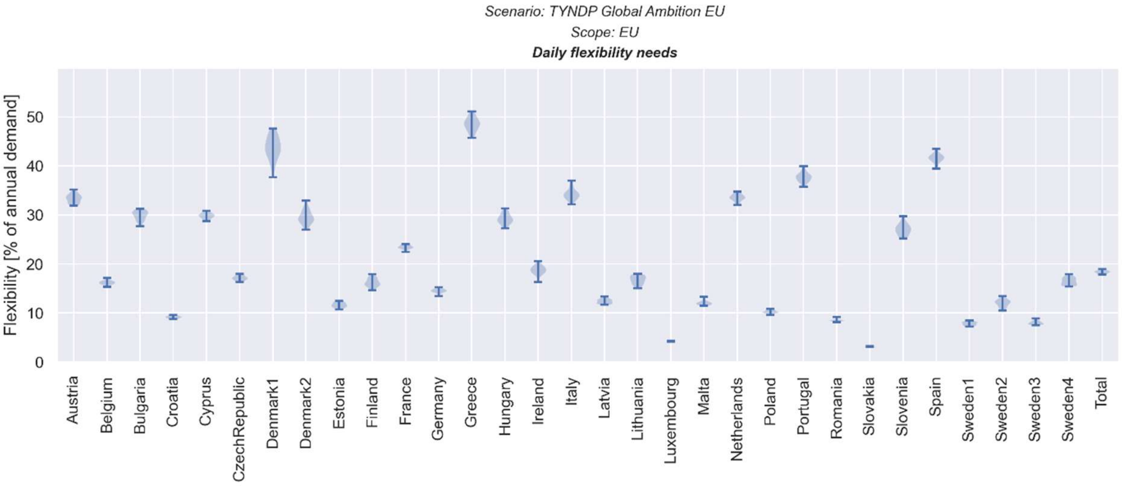


Figure 4.23: Weekly flexibility needs - China CEC Scenario

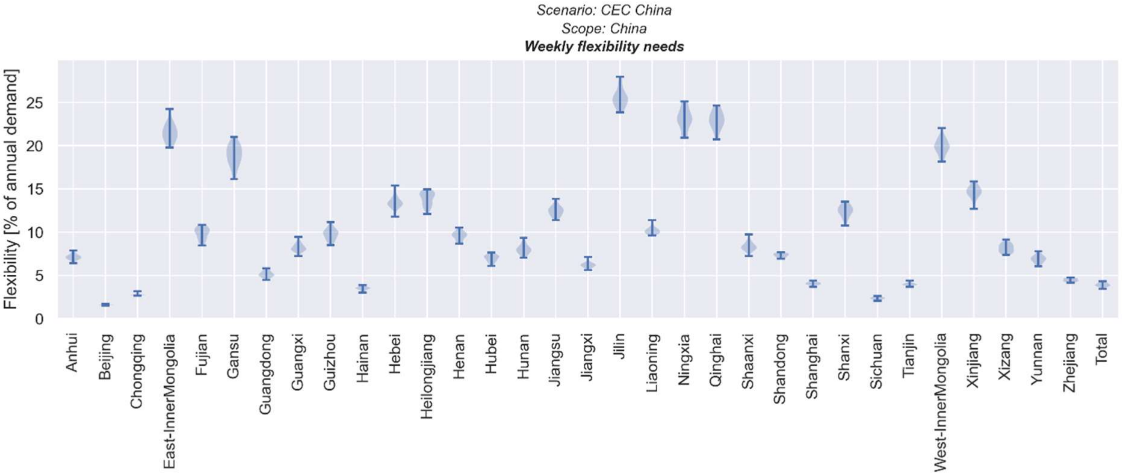


Figure 4.24: Weekly flexibility needs - EU Global Ambition Scenario

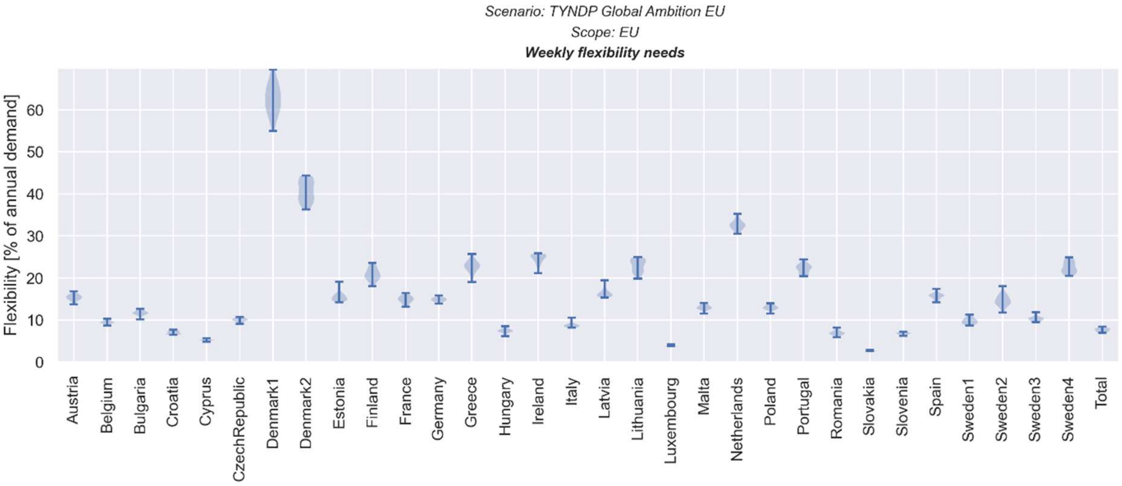


Figure 4.25: Annual flexibility needs - China CEC scenario

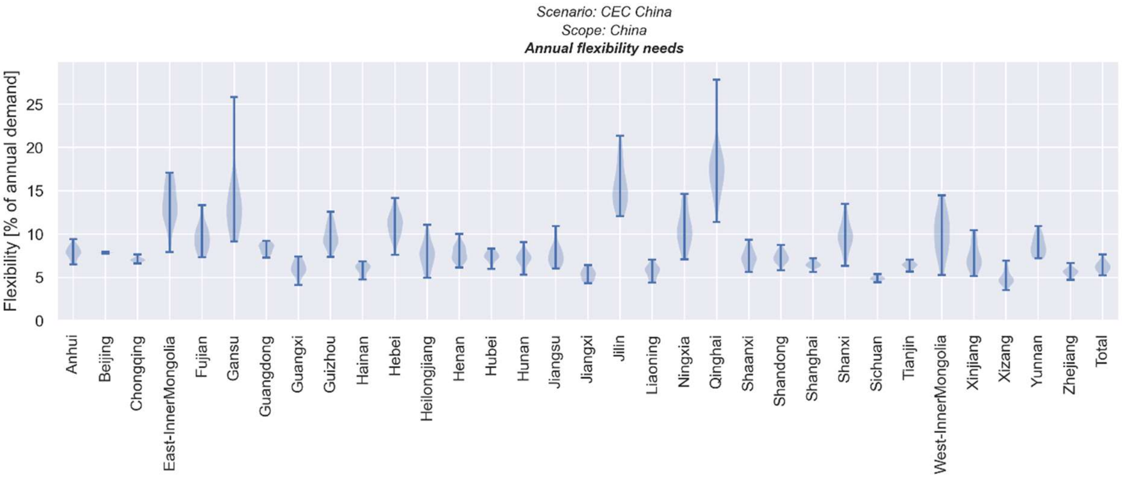
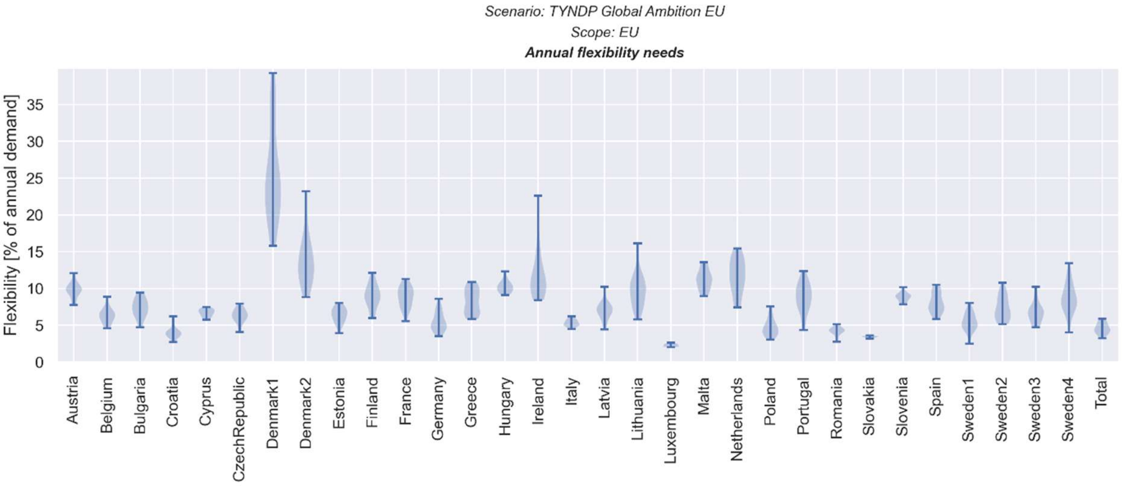


Figure 4.26*:* Annual flexibility needs - EU Global Ambition Scenario



Residual load droughts have short time horizons. Of the three time scales considered[13], the daily pattern of energy generation and consumption requires the most flexibility. This is also in line with the conclusion of the energy drought analysis. Short term flexibility needs are less sensitive to annual weather variations compared to long term flexibility needs where seasonality plays a larger role.

Depending on the timescale, different solutions to solve the flexibility needs are likely to be favoured. Short-term flexibility can for instance be delivered by batteries or flexible sources of energy generation or demand that can ramp up/down quickly, whereas long-term flexibility is better provided by other means, e.g. pumped hydro. Overall, our analysis can give an idea of which types of flexible assets can bring value to the system and thus increase energy security.

VRE penetration versus flexibility needs

The following Figures illustrate the flexibility needs as a function of VRE penetration level in Chinese provinces and in EU countries (see Figure 4.27 – Figure 4.32).

Note (*Figure 4.27****-****Figure 4.32****):** Flexibility needs at daily, weekly, and annual time scales. Legend: VRE dominated by solar PV: yellow dots. VRE dominated by wind: blue dots. Mixed VRE: green dots. The y-axis is percentage of annual energy demand.*

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[13] Daily, weekly, and annual timescale.

Figure 4.27: Daily flexibility needs vs VRE penetration - China CEC scenario

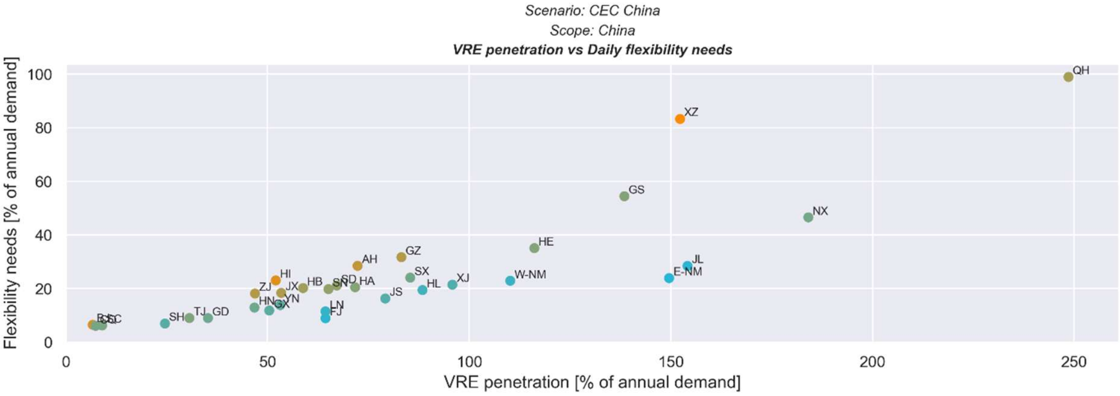


Figure 4.28: Weekly flexibility needs vs VRE penetration - China CEC scenario

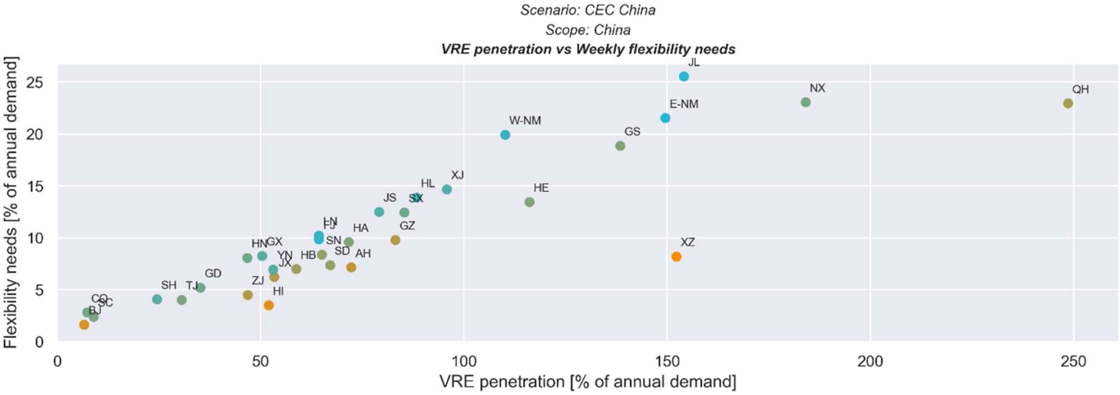


Figure 4.29: Annual flexibility needs vs VRE penetration - China CEC scenario

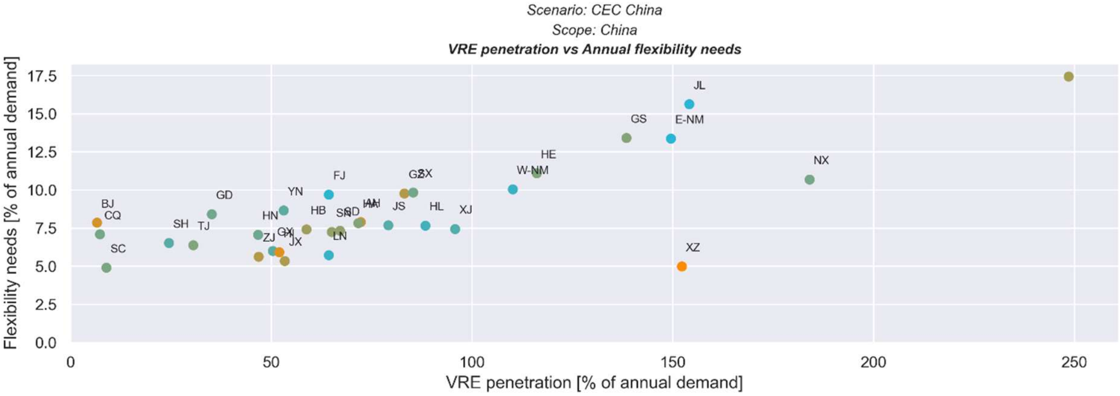


Figure 4.30: Daily flexibility needs vs VRE penetration - EU Global Ambition Scenario

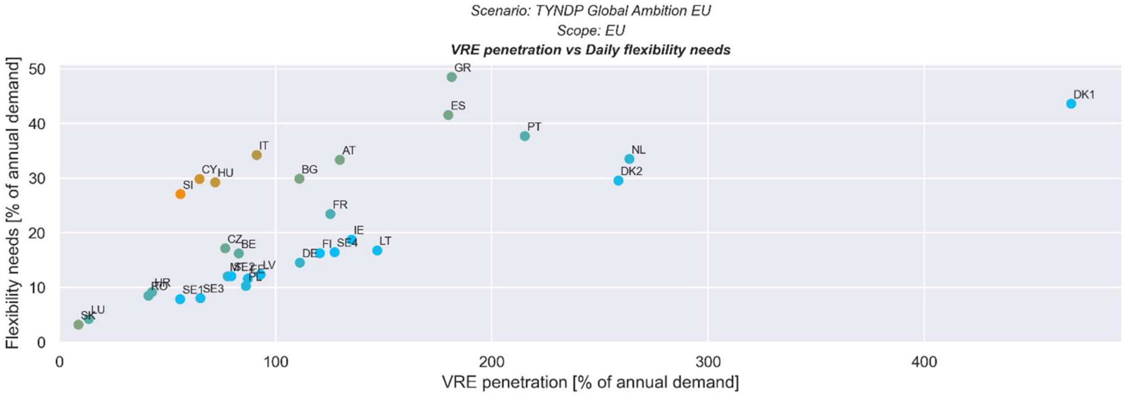


Figure 4.31: Weekly flexibility needs vs VRE penetration - EU Global Ambition Scenario

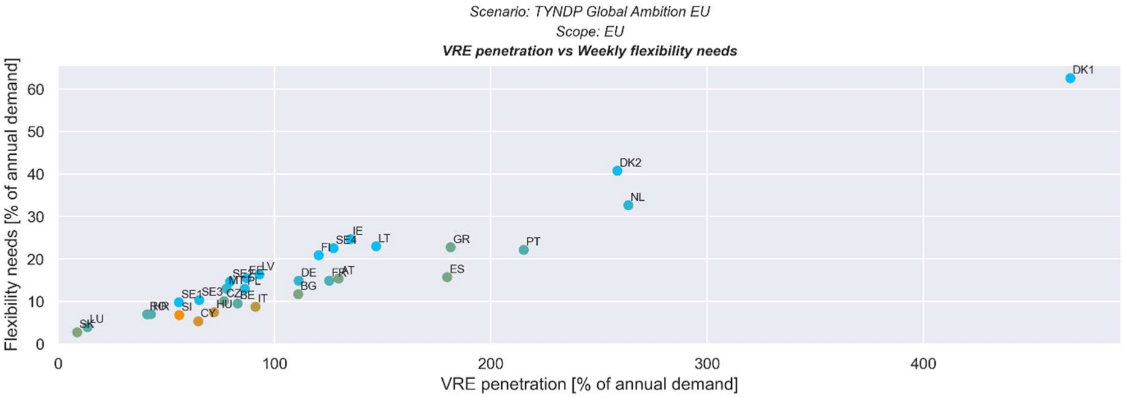
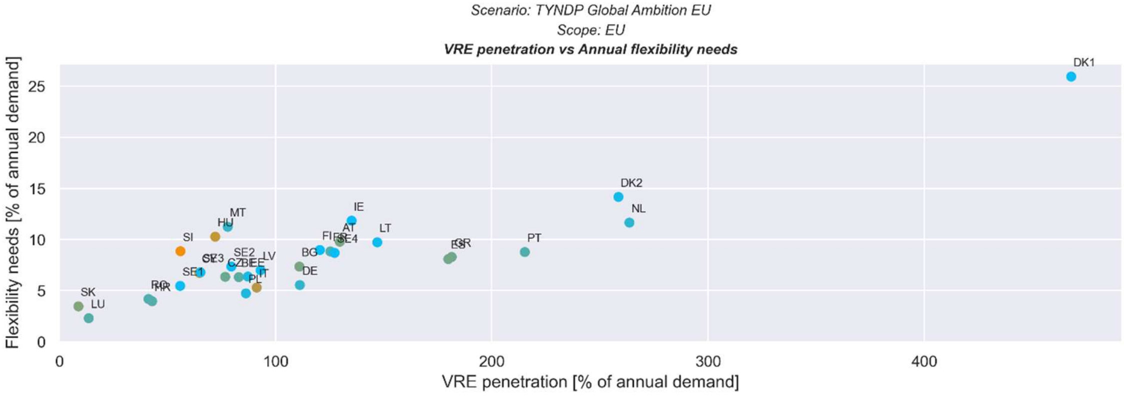


Figure 4.32: Annual flexibility needs vs VRE penetration - EU Global Ambition Scenario



A general observation is that a higher VRE penetration requires more flexibility from the power system.

Regions with a high share of solar PV generation require greater daily flexibility, whereas regions dominated by wind need more flexibility on a weekly scale. As is evident in the Figures above, regions with a high share of VRE generation coming from solar PV (indicated by a yellow dot) will generally have higher daily flexibility needs than regions dominated by wind (indicated by a blue dot). The opposite is the case when considering the weekly timescale, where regions with a high share of wind will need more flexibility than regions with a high share of solar PV. This conclusion follows the result of the energy drought analysis which shows that many of the solar energy droughts last less than a day, whereas wind energy droughts typically last several days.

For the annual timescale, the picture is a little more blurred. In China, regions dominated by wind typically have higher needs than regions dominated by solar PV. In the EU, no clear tendency can be observed.

Key findings – Impact of weather patterns on VRE resources:

(Comparative analysis of the power system adequacy contribution of VRE resources deployed in Europe vis-à-vis China)

When 'China/EU' is mentioned here, it refers to the total power system in China/EU. 'Regional level' refers to provinces/countries.

- Wind is generally more variable than solar PV at an annual timescale. The level of generation variability for the whole of mainland China/whole of EU is smaller for regions, which shows that irregularities, as expected, tend to flatten when considering larger geographical areas.
- For the limited hours with high residual peak, the spot market is not expected to provide incentives to build backup power (e.g. natural gas turbines). Capacity mechanisms could provide a remuneration for capacity being kept ready to cover the residual load deficit.
- Wind energy droughts have a shorter duration in the EU than in China, because of a better wind climate in the EU and the higher share of offshore wind capacity, which tends to be in areas with higher wind availability.
- Solar PV duration curves are very similar for China and the EU; however, droughts have a shorter duration in China than in Europe.
- The EU on average experiences a larger seasonal impact over the year, i.e., because of long nights (no solar) during winter due to its higher latitude. However, most of the solar droughts tend to be short-term with a duration of less than one day.
- The durations of residual load droughts are generally very short (most events last less than a day) in both China and the EU.
- The need for long-term baseload capacity is limited, but more flexibility resources would be useful to fill VRE generation gaps. Despite wind and solar droughts lasting several days, the daily demand pattern 'breaks' the residual load drought into shorter ones.
- At a regional level (EU Member States and Chinese provinces), energy droughts tend to be longer. This highlights the importance of inter-regional transmission capacity/interconnectors and electricity markets.
- Residual load droughts in China and the EU have short time horizons, which could be covered by batteries or flexible sources of energy generation or demand that can ramp up/down quickly.
- Regions in China and the EU with a high share of solar PV generation require greater daily flexibility, whereas regions dominated by wind need more flexibility on a weekly scale.

4.5 Sensitivity of results with regard to scenario

The results in Chapter 4.4 are based on the China CEC scenario (2060) and the EU Global Ambition Scenario (2050). However, we have calculated results for two additional scenarios described in Figure 4.1 and Table 4.1: the CETO carbon neutral scenario (CNS2) and the EU Distributed Generation Scenario.

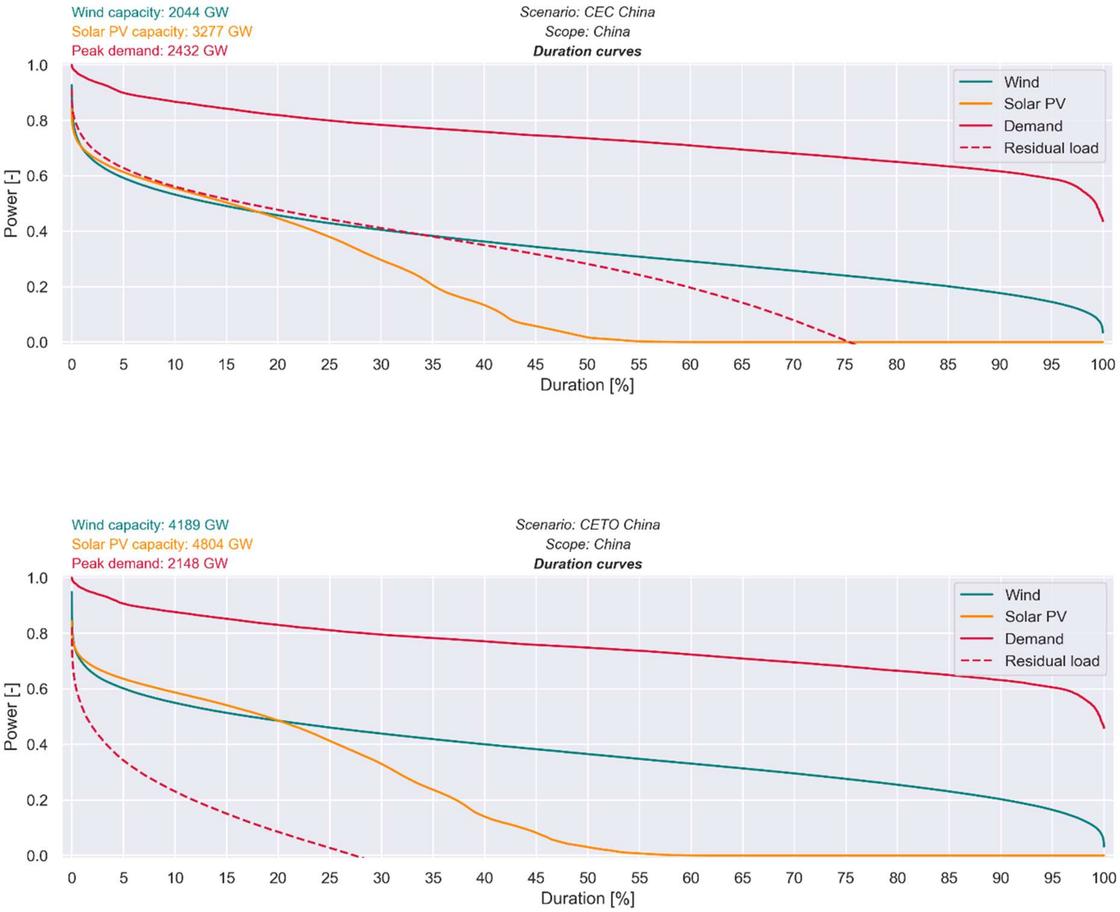
All results for WP2 can be found in the separate attachment: ANNEX, Energy security in the context of energy transition – Lessons and Challenges within Europe and within China.

For illustrative purposes and to demonstrate the impact of selection of scenario we will discuss and compare results for China based on the CEC scenario and the CETO scenario, respectively. The reason for this choice of comparison is the relatively big difference of VRE deployment in the two scenarios. The difference between the two EU scenarios is relatively minor with marginal deviation in the results.

Duration curves

The duration curves for the total system of China in the two scenarios are shown in Figure 4.33.

Figure 4.33: Comparison of duration curves in two scenarios (CEC and CETO)

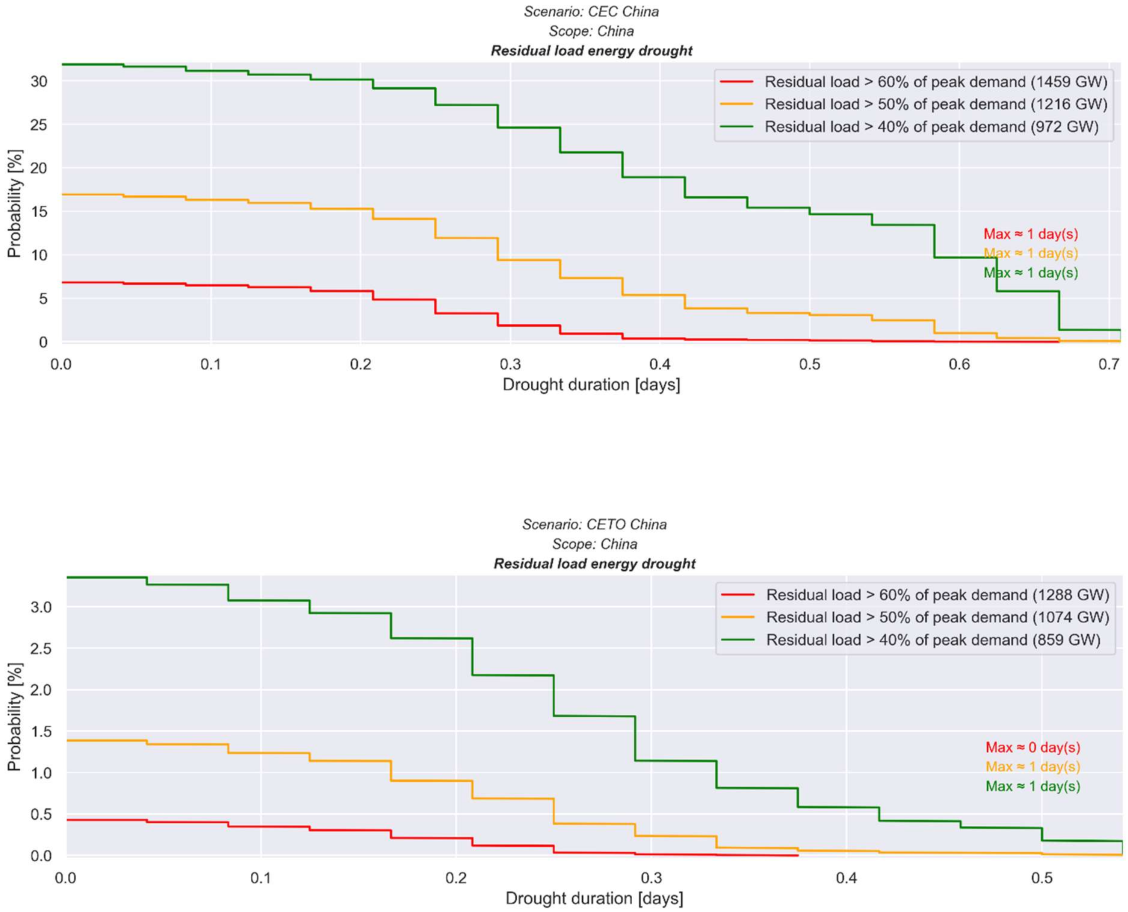


It follows that duration curves for demand, wind and solar are very similar while duration curves for residual load are very different. The reason is that wind and solar duration curves depend on weather patterns which are the same in the two scenarios. (There may, however, be small differences due to changes in relative installed capacities of wind and solar in the different provinces).

The reason for the difference with regard to residual load is of course the huge discrepancy in VRE deployment. In the CETO scenario, VRE alone can cover about 70% of demand while the corresponding number in the CEC scenario is about 25%.

Residual load energy drought

Figure 4.34: Comparison of residual load energy drought in two scenarios (CEC and CETO)



A comparison of residual load energy droughts is shown in Figure 4.34. It is interesting to see that the maximal durations of droughts (total power system) are quite similar in the two scenarios and less than one day. However, the probabilities are very different, with much higher probabilities for droughts to occur in the CETO scenario which has far larger installed capacities of VRE (see Table 4.1).

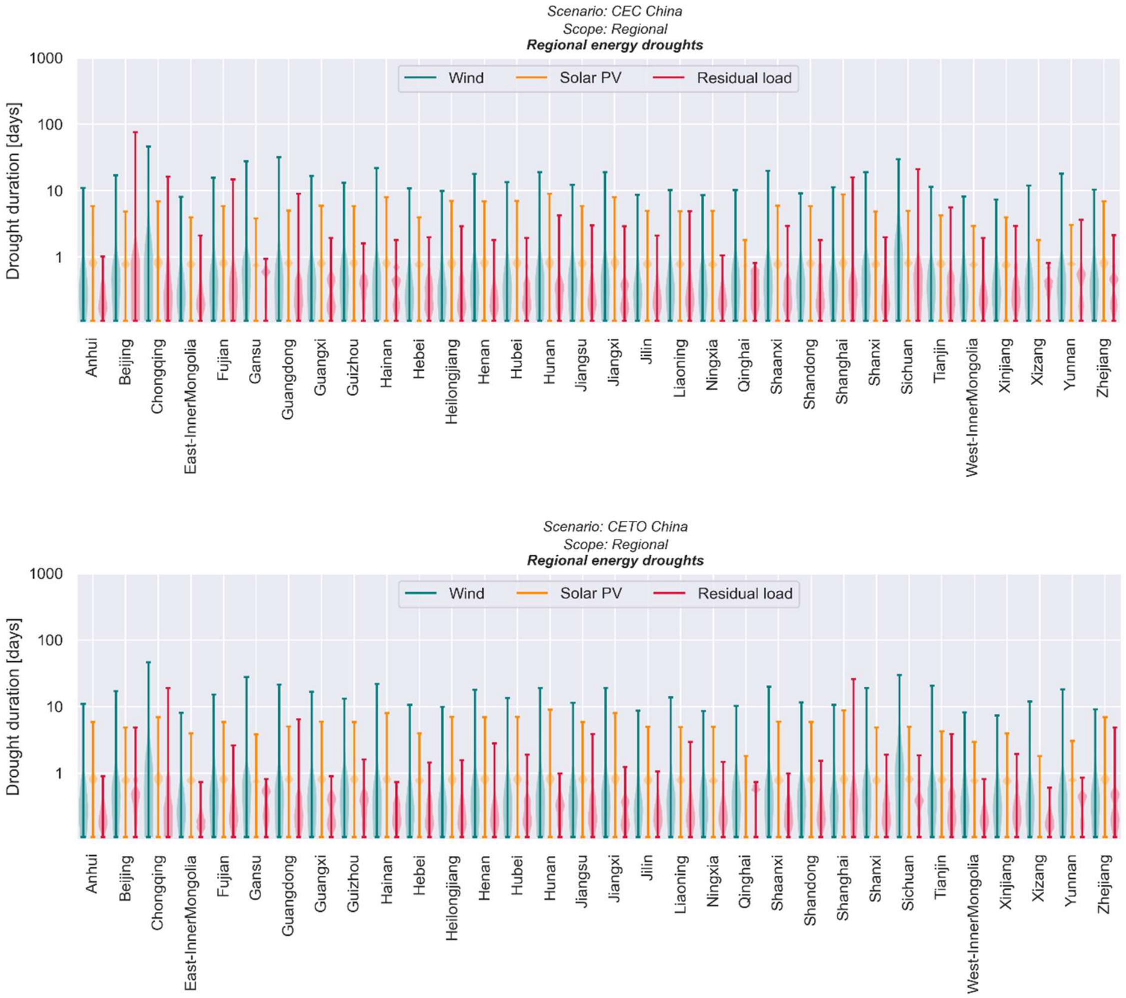
Regional energy droughts

Maximal regional energy droughts are compared in Figure 4.35. It follows that the duration of droughts for wind and solar are quite similar in the two scenarios. This is to be expected, given that wind and solar droughts depend on the wind and solar weather patterns in a specific province and not on installed capacities.

Comparison of maximal provincial residual load droughts show some deviations between the two scenarios. The reason for this is the differences in installed VRE capacities at a provincial level in the two scenarios. It is interesting to note that even if the maximal provincial load droughts deviate at a provincial level in the two scenarios the maximal residual load droughts are of a similar size for the system as a whole (compare with Figure 4.34). This can be explained by the assumption of no transmission bottlenecks between provinces.

Still, it should be noted that the residual load droughts show a much higher probability to occur in the CEC scenario.

Figure 4.35: Comparison of maximal regional energy droughts in two scenarios (CEC and CETO)

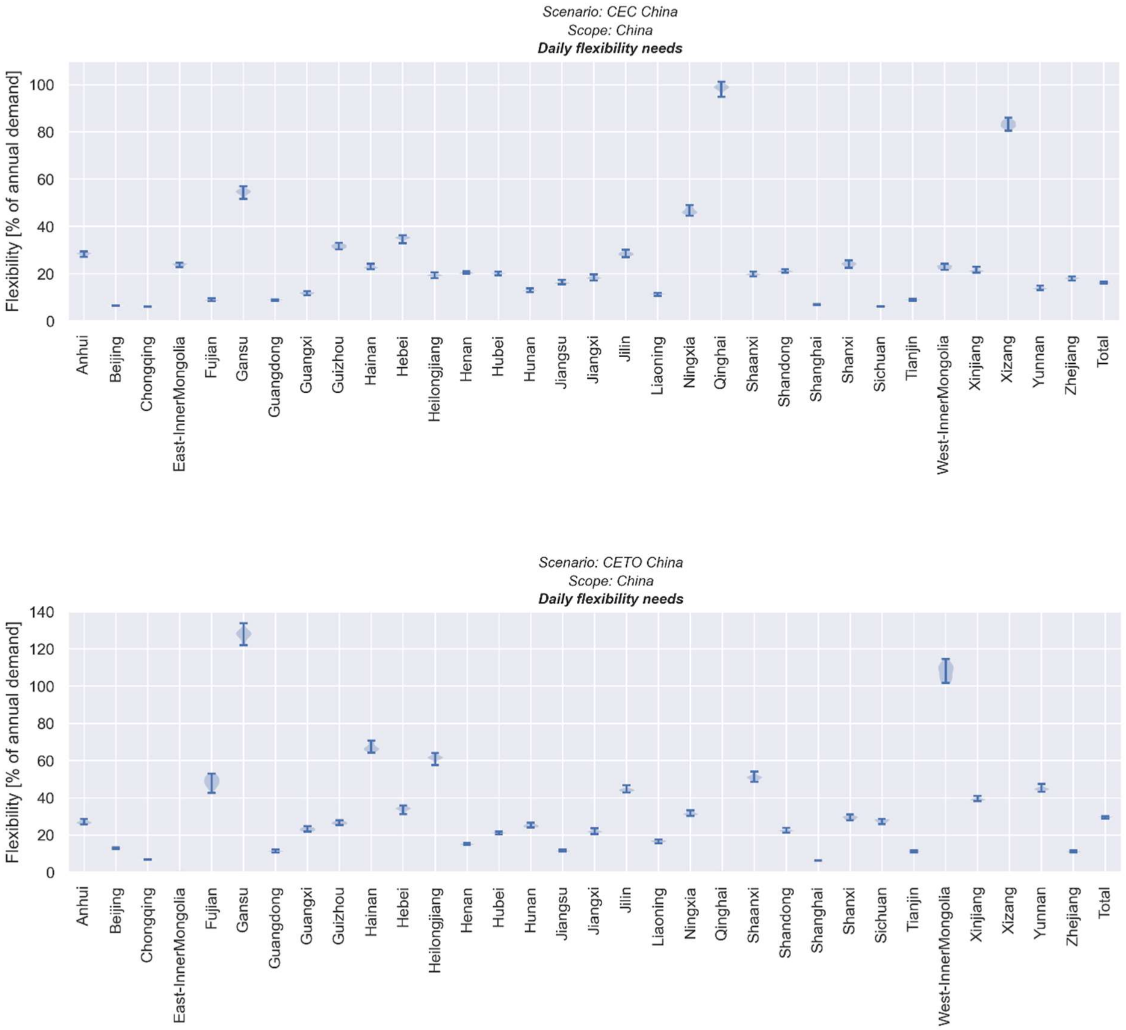


Note that the y-axis is logarithmic. Residual load >50% of peak demand and wind/solar generation <30% of capacity. Note that the y-axis is logarithmic.

Daily flexibility needs

Daily flexibility needs are compared in Figure 4.36. As expected, the general pattern is that the needs are highest in the CETO scenario with the largest (on average) installed capacities of VRE, e.g., Fujian, Gansu, Hainan and West-Inner Mongolia have higher needs. Also, the 'total' at the far right of the Figure shows a higher value in the CETO scenario.

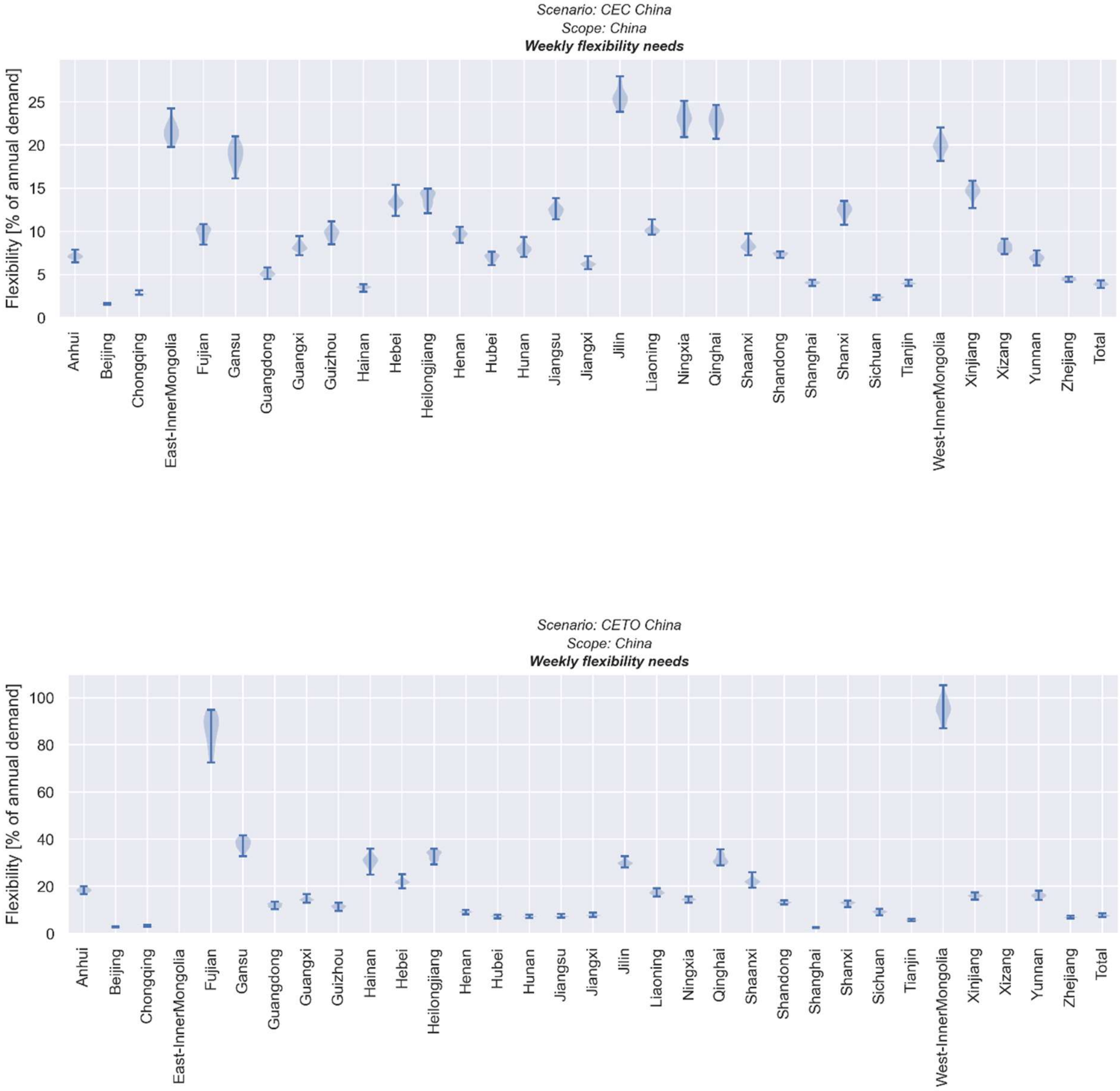
Figure 4.36: Comparison of daily flexibility needs in two scenarios (CEC and CETO)



Weekly flexibility needs

Weekly flexibility needs are compared in Figure 4.37. As expected, here too the general pattern is that the needs are highest in the CETO scenario with the largest (on average) installed capacities of VRE. Note that the y-axis is scaled differently in the two scenarios. E.g., Fujian, Gansu, Hainan and West-Inner Mongolia have much higher needs.

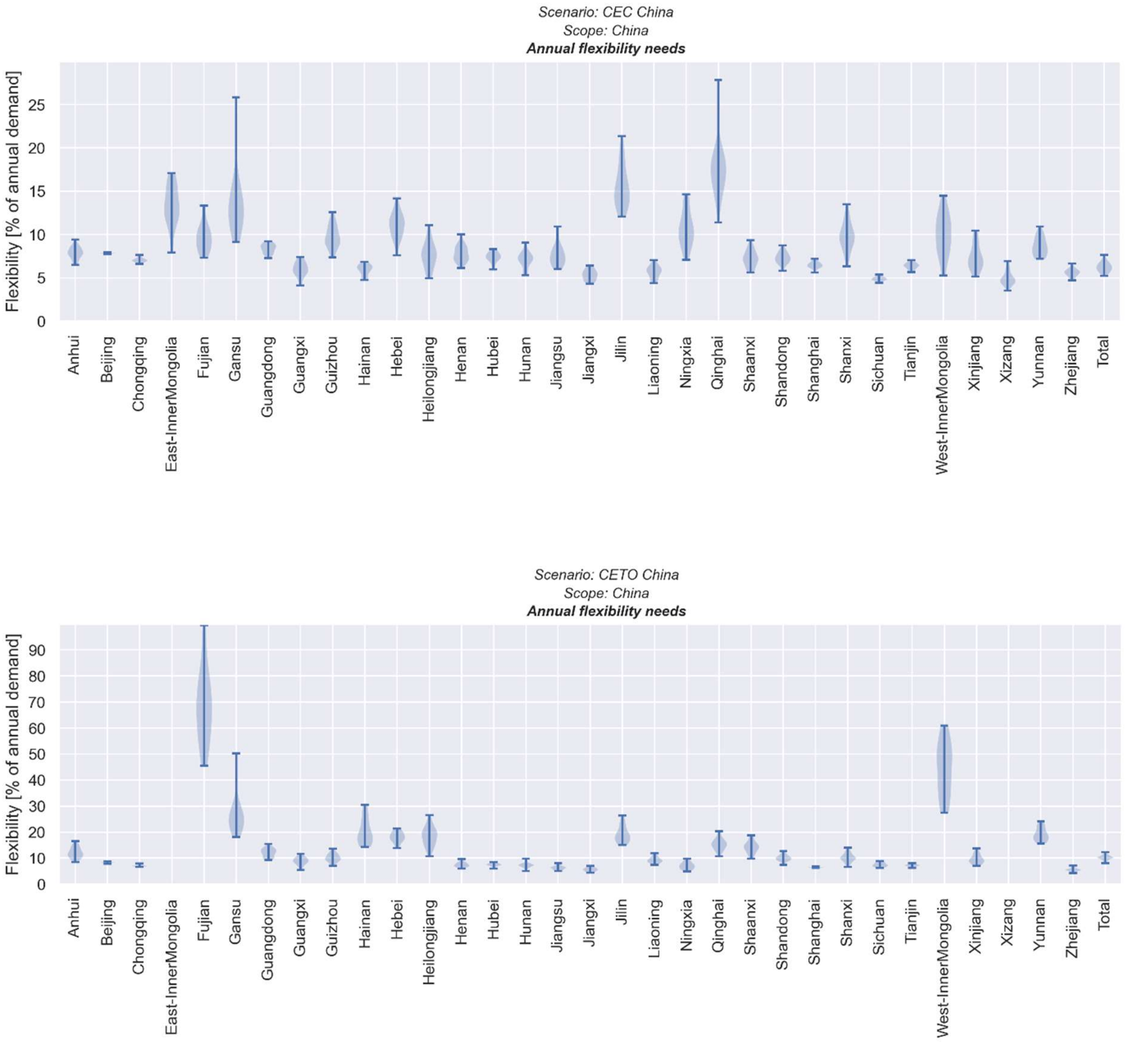
Figure 4.37: Comparison of weekly flexibility needs in two scenarios (CEC and CETO)



Annual flexibility needs

Annual flexibility needs are compared in Figure 4.38. Again, as expected the general pattern is that the needs are highest in the CETO scenario with the largest (on average) installed capacities of VRE. Note that the y-axis is scaled differently in the two scenarios.

Figure 4.38: Comparison of annual flexibility needs in two scenarios (CEC and CETO)



4.6 Hydropower

Hydropower is an important energy and flexibility source in both Europe and China with varying energy production. While we do not have the specific data to conduct a similar study with run-of-river hydro as we have with wind and solar PV, in the following we give a short insight into hydropower in Europe and China.

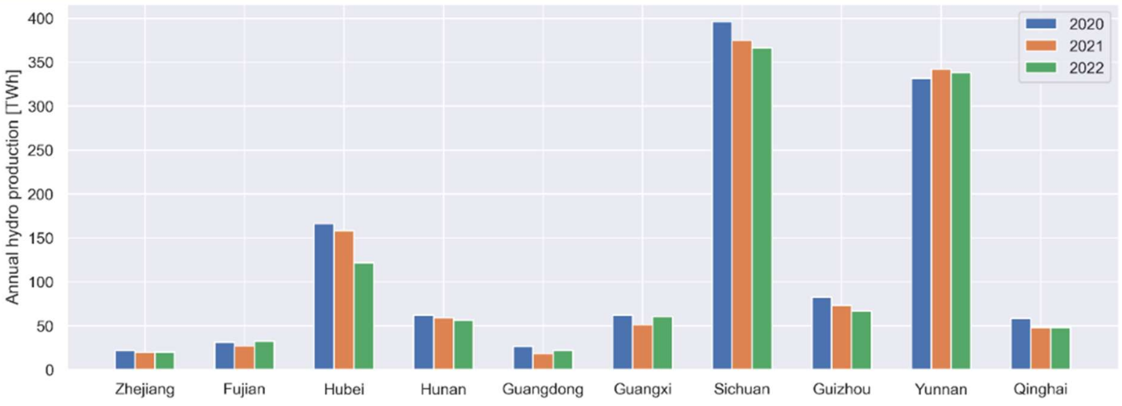
Hydropower in Europe

As the largest renewable electricity source, hydropower is an important energy source in Europe. According to ENTSO-E (2023a), in 2021 hydropower accounted for 43% of Europe's renewable electricity production and provided 16% of total electricity generation. Major hydropower producers are Norway, Sweden, France, Italy and Austria.

Hydropower in China

Figure 4.39 gives an overview of annual hydropower generation in 2020, 2021 and 2022 in China's key hydropower provinces.

Figure 4.39: Annual hydropower generation in China (TWh)

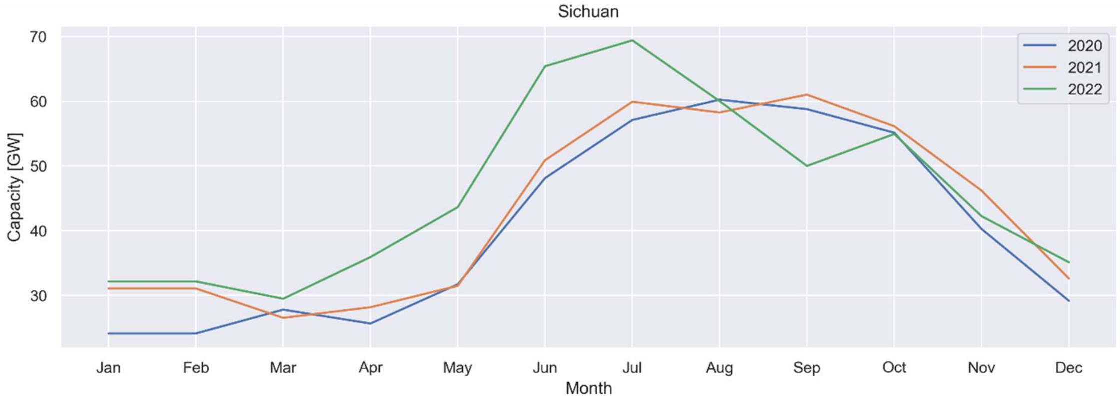


Source: CEC.

Sichuan and Yunnan provinces, situated at the Yangtze River, show the highest annual generation.

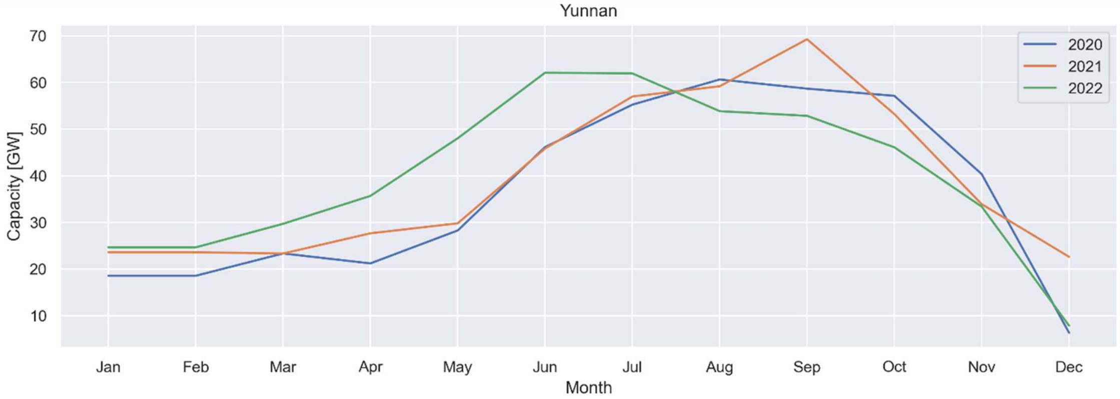
Figure 4.40 and Figure 4.41 show the average capacity factor of hydro generation in each month of the year for Sichuan and Yunnan in 2020-22, respectively. It follows that generation is highest during summer and early autumn, when both the inflow to the power stations and consumption are at their peak.

Figure 4.40: Capacity (GW) of hydropower generation over the year in Sichuan



Source CEC.

Figure 4.41: Capacity (GW) of hydropower generation over the year in Yunnan



Source: CEC.

A note on hydropower evaluation

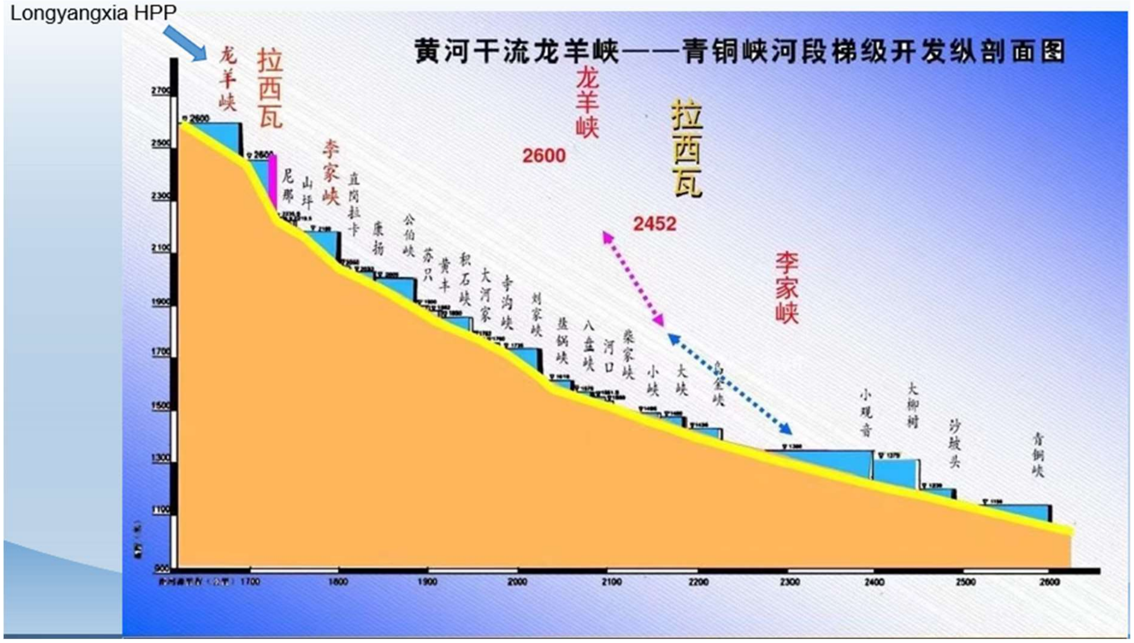
The intention had been to include hydropower in the analyses of e.g., residual load drought and flexibility needs, as was shown for VRE wind and solar PV. However, the generation profiles which are shown above for hydropower in China are a mix of generation from run-of-river hydropower and hydropower with reservoirs.

If specific statistics were available for run-of-river hydro which in principle is a VRE energy source like wind and solar PV, then it would have been possible to include some of that data in this analysis. However, we do not have access to that data.

Another important barrier to considering hydropower in the same detail as wind and solar PV is the complexity that can be involved in operating a hydropower resource. An example is the restriction on water levels in rivers and reservoirs because water is used not only for power generation but also for irrigation, flood management and drinking water etc.

One particular consideration is that of cascading hydropower along a river which sets strict boundaries on each power station's generation due to conditions for downstream power stations' generation. An example is shown in Figure 4.42, with hydropower stations along the Yellow River and Longyangxia power station (4 x 320 MW units) situated upstream.

Figure 4.42: Cascading hydropower plants at the Yellow River with Longyangxia hydropower plant (HPP) situated upstream



Source: CEC.

5. Lessons on energy security in the EU and China

The net-zero energy system in 2050/2060 will no longer be dependent on fossil fuels, or only to a limited extent, so that energy price shocks such as the oil crisis in the 1970s or the recent natural gas shortages will have less of an impact on the system. However, the energy system of today and the mid-transition energy system still face a certain degree of fossil fuel dependency. As described in Chapters 3, 4, 5 and 6, the energy transition brings with it further risk factors. It can be expected that energy crises of various kinds will continue to affect energy security in the mid-transition. This chapter describes examples of measures taken by the EU and by China to respond to concrete energy security threats and the lessons learned with regard to mitigating energy security risks.

5.1 Lessons from the 2022 natural gas crisis in the EU

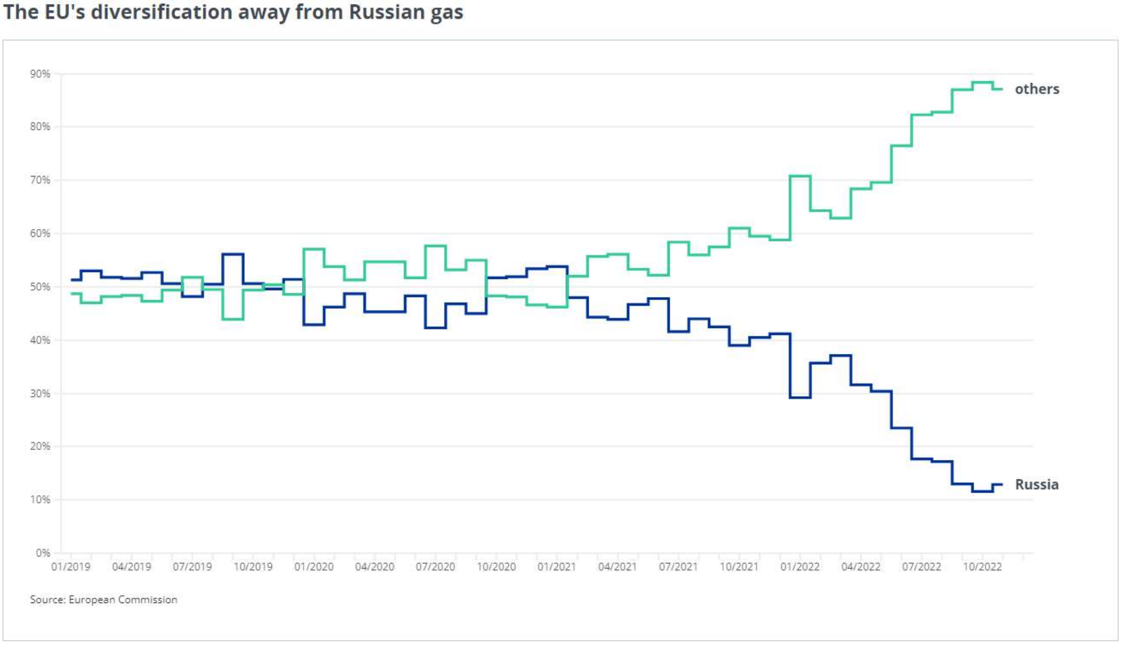
Lesson E1: Diversification of supply, aggregation of demand and a market correction mechanism

The key lesson learned is the importance of diversifying natural gas supply sources to reduce dependency on a single supplier, as demonstrated by the EU's response to the reduction in Russian natural gas imports by increasing LNG imports and gas supplies from other countries and implementing mechanisms such as 'AggregateEU' for demand aggregation and joint gas purchases, along with a market correction mechanism to address extraordinarily high prices during times of scarcity.

Diversification of supply

Europe has been heavily dependent on Russian natural gas, oil, and coal supplies for many years. Russian natural gas covered between 40% and 50% of the EU’s natural gas demand between 2019 and February 2022 (see Figure 5.1). After the geopolitical conflict between Russia and Ukraine started on 24 February 2022, the share of Russian natural gas was steadily, and significantly, reduced to 13% by November 2022.

Figure 5.1*: Share of Russian gas supplies to the EU 2019-22*



Source: European Council (2023).

- The decrease in Russian natural gas imports was the result of multiple political decisions in both the EU and in Russia. Russian natural gas was supplanted by multiple other sources of natural gas:
- Increased LNG imports from mainly US, Qatar and Nigeria.
- Increased gas imports from Norway, UK and Algeria.
- Natural gas demand reductions due to high prices.

As of November 2022, LNG imports and imports from Norway accounted for roughly 25% each of all EU imports, while Russian gas supply, including LNG, is also 25%. Algeria represents 12% of the supply, and the remaining 13% is a mix of minor imports from other countries.

Aggregation of demand – AggregateEU

In a further response to the natural gas shortages, the EU Energy Platform was launched in April 2022 and 'AggregateEU', a mechanism for demand aggregation and joint gas purchase at European level was formally adopted on 19 December 2022 by the Energy Ministers of the EU. The platform has three objectives, all intended to enhance the EU's security of natural gas and LNG supply: i) demand aggregation and joint purchase of gas, ii) most efficient use of infrastructure, and iii) international outreach. By aggregating and coordinating the demand in Member States, the platform prevents individual Member States from outbidding each other and using the aggregated weight of the Member States to negotiate better purchase conditions. In order to diversify natural gas supply, the platform facilitated Memoranda of Understanding with the US, Azerbaijan, Egypt and Norway as key gas exporting countries. The purchase of gas is hereby not made by the

European Commission itself, but by companies through the PRISMA platform, which is a gas capacity platform operated by a private company owned by a number of European transmission system operators. The focus of the platform in 2023 is to purchase sufficient natural gas to fill the gas storage facilities for the winter 2023-24. During the first two tendering rounds, over 93% of the expressed demand was partially or entirely matched with supply (European Commission, 2023c).

Market correction mechanism

The European natural gas markets are built on free market mechanisms that govern supply and demand. During the natural gas crisis, the EU reaffirmed its trust in the free market by not radically changing it in times of crisis. It is now clear that the market reactions that include increased LNG imports, more pipeline imports and demand savings, managed to supplant almost all the Russian natural gas supply.

In December 2022, the EU decided to implement a market correction mechanism, given the prevailing extraordinarily high gas prices, to mitigate against the adverse economic consequences of scarcity pricing. The mechanism can be activated from 15 February 2023, if two conditions are met.

- The front-month Dutch TTF (virtual trading point for natural gas) future price must exceed EUR 180/MWh for three consecutive days.[14]
- Additionally, a reference price is defined which aims to reflect the LNG import spot price in Europe. The TTF settlement price must be EUR 35/MWh higher than this reference price for the same three consecutive days. This condition acts to anchor the TTF futures settlement price to the LNG spot price, so that the impact of futures speculation is limited to prevent excessively high gas prices that exceed world market prices.

Fundamentally, this price level of EUR 180/MWh is 10 times higher than the average price between 2015 and 2020, showing a high price level relative to previous average natural gas price levels (ACER, 2023).

Figure 5.2 illustrates the market correction mechanism with historical natural gas prices. The two activation conditions were met in September 2022 but the price has since dropped below the EUR 180/MWh activation level.

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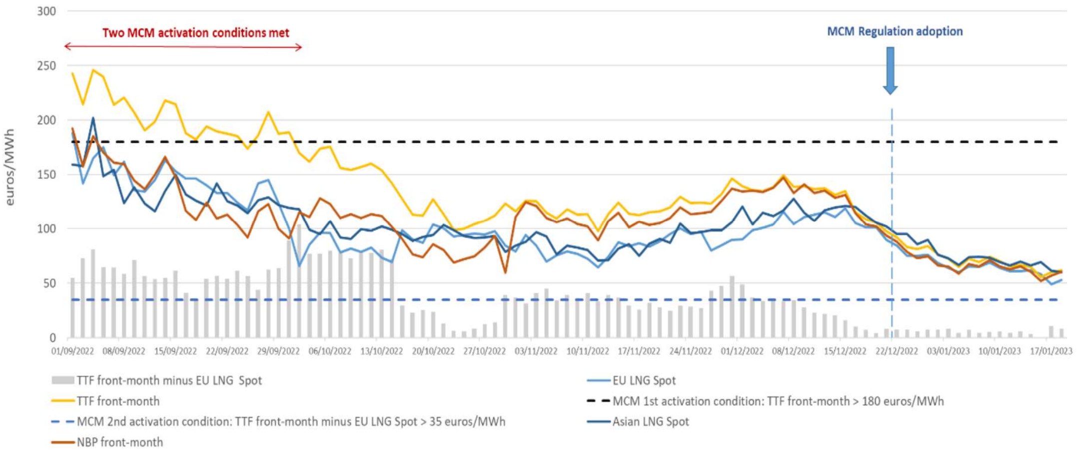
[14] *A future is a financial contract to exchange a commodity at a fixed price and at a specific time in the future.*

Figure 5.2: Front-month TTF, NBP, EU LNG and Asian JKM reference price evolution (EUR/MWh)



Source: ACER (2023).

5.2 Lesson from reforming the electricity market design in response to the recent energy crisis in the EU

Lesson E2: Emergency intervention and long-term market reform

While the current electricity market design was not to blame for the energy crisis, it helped mitigate its impact. Interfering heavily with liberal market price signals could jeopardise the benefits achieved over the years. To address surging electricity prices, the EU introduced an inframarginal generator market revenue cap, ensuring additional revenues were redistributed to consumers, with a focus on supporting renewables and reducing dependence on volatile fossil fuel prices in the long-term market reform.

Emergency intervention

In response to the high electricity market prices observed since September 2021, the European Union consulted the EU Agency for the Cooperation of Energy Regulators (ACER) on its assessment of the current electricity market model.

In its report, ACER (2022) concluded that the crisis and ensuing high prices in the gas sector were directly linked to the spike in electricity market prices due to the considerable contribution of natural gas fired power plants in the electricity generation mix when the demand was at its highest or when nuclear and renewable technologies could not meet demand. Specifically, ACER declared the current energy crisis essentially to be a ‘gas-price shock’.

While ACER's (2022) assessment led to the *Emergency Intervention to Address Energy Prices* in October 2022, its main focus was to provide a longer-term perspective on the EU electricity market design in terms of its resilience and any necessary adjustments in regard to its fit-for-purpose aspects. Thirteen measures were put forward for consideration by policy makers, under the umbrella of the six following focus areas which could offer opportunities to future-proof the current market design:

1. Ensure short-term electricity markets work better everywhere.
2. Drive the energy transition through efficient long-term markets.
3. Increase the flexibility of the electricity system.
4. Protect consumers against excessive volatility whilst addressing inevitable trade-offs.
5. Tackle non-market barriers and political stumbling blocks.
6. Prepare for future high energy prices in ‘peace time’; be prudent towards wholesale market intervention in ‘war time’.

ACER’s evaluation can be summarised as follows: the current electricity market design, despite questions being raised during the developing geopolitical upheavals, was not to blame for the crisis. Rather, the market mechanisms mitigated the crisis. To have intervened and interfered with liberally-integrated market price signals could have jeopardised the benefits achieved over the course of more than 20 years, while also imposing further economic burdens during the broader green transition.

In an intervention intended to rapidly tame the effects of surging wholesale and retail electricity prices on final electricity consumers, the EU introduced an inframarginal generator market revenue cap of EUR 180/MWh (see Figure *5.3*) ensuring that additional revenues were redistributed to final users as financial support measures. The cap on market revenues was set to apply until June 2023, from its application in December 2022. The price cap of EUR 180/MWh was assessed as being consistently higher than the prevailing LCOE for the relevant generation technologies, and thus would not jeopardise investments in new inframarginal capacities.

The cap does not apply to technologies with high marginal costs due to the prices of their input fuels, such as gas and hard-coal-fired power plants, because the measure would impact their economic viability and would reduce the incentive for market participation.[15] The generic principles of the emergency intervention measure are illustrated in Figure *5.3*.

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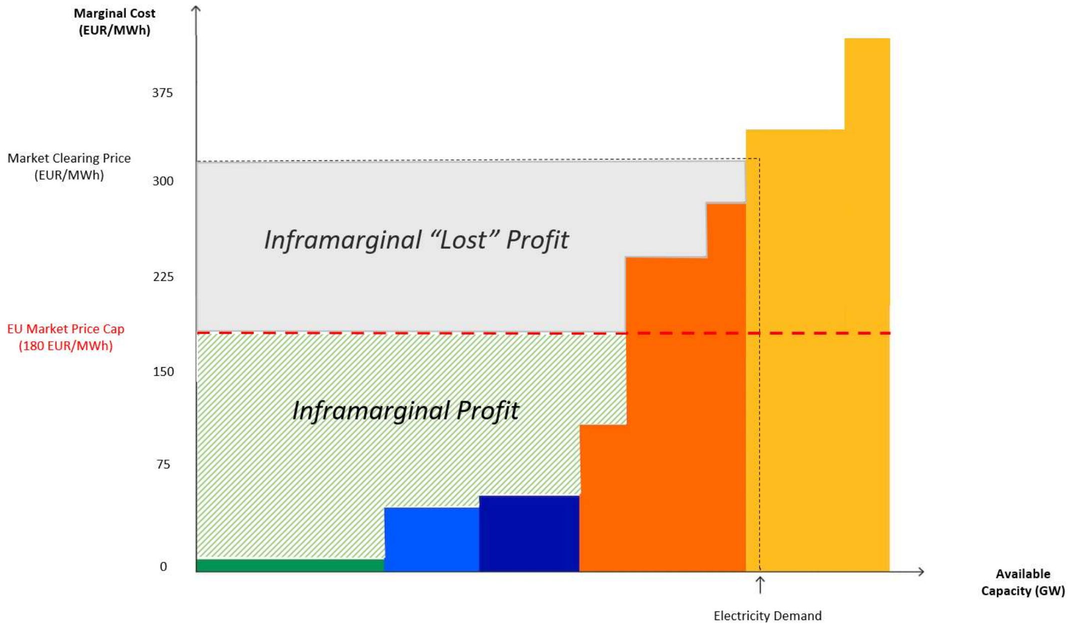
[15] Further exemptions can be found in Council Regulation (EU) 2022/1854, paragraphs 32 to 42.

Figure *5.3*: Energy market intervention (price cap mechanism)



Source: Adjusted from de Boer & Stet (2022).

Long term market reform

The EU is currently debating a revised electricity market design against the backdrop of the outbreak of conflict in Ukraine and surging electricity prices across Europe. Following a consultation process, the European Commission proposed a targeted reform in March 2023. The reform is intended to make electricity prices less dependent on volatile fossil fuel prices, decrease the investment uncertainty in electricity markets and to accelerate the build-out of home-grown and competitive renewables.

In July 2023 the European Parliament's Industry, Research and Energy Committee (ITRE) voted on the reform. The ITRE largely backed the European Commission's proposal for a targeted reform of the EU electricity market design (WindEurope, 2023).

The ITRE Committee voted to **maintain the merit order system and to avoid inframarginal revenue caps** which would fragment the internal energy market and undermine investor confidence. Crucially, the reform would allow different routes to market for renewable electricity: these are Contracts for Difference (CfD), renewable Power Purchase Agreements (PPA), and merchant investments. Having these different routes to market is vital in view of the huge volume of investments that will be needed by 2030.

In parallel, the 27 EU Member States (represented by the national energy ministers in the Council of the European Union) reached an agreement on 17 October 2023 on their negotiating mandate as regards the EU electricity market design revision. The next step will be for the Council and the European Parliament to negotiate the final deal before it is formally adopted by the Council and the European Parliament. The EU electricity market design reform needs to be finalised by the end of 2023 as mandated by EU Heads of State and Government and is expected to be implemented in early 2024.

5.3 Lessons from China's energy security risks

Lesson C1: Diversification of imported fuels is important for energy security

China has effectively diversified its fuel imports, including oil, gas, coal, and uranium, from various international sources, in addition to maintaining a domestic supply of these resources.

China has successfully diversified its fuel imports, as follows:

- Oil: imports from Saudi Arabia and Russia.
- Gas: LNG from Australia (top supplier), Qatar, Malaysia; pipeline gas from the Commonwealth of Independent States (CIS) and Russia.
- Coal: imports mainly from Indonesia, Russia, Australia, the US, and Colombia.
- Uranium: supply from foreign equity overseas mining ventures and supply from open market purchases.

China also has its own domestic supplies of oil, gas and coal.

Lesson C2: Importance of diversification of supply of critical materials for energy system transformation

China plays a crucial role in the supply chains for clean energy technologies, giving it a strategic advantage in accessing critical materials for the energy system transformation.

China is in a strong position regarding access to critical materials. It has a major role in several clean energy technology supply chains such as EV deployment, PV systems, and wind and electrolyser installations - particularly at the mid- and downstream levels.

Lesson C3: Uncoordinated technology transition must be avoided

To mitigate risks, it is crucial to avoid an uncoordinated transition of technologies, given the challenge when it comes to determining the optimal timing and progress of the relevant processes.

The pace at which phase-in/phase-out process of technologies takes place is risky, as there are no objective means to determine the best timing and progress of such processes.

An instance of this situation occurred in China in 2017, after implementation of an action plan to prevent and control air pollution (Zhou, 2018). The plan entailed both coal power plant retrofitting as well as coal-to-gas switching of ‘dispersed coal’ boilers that provided industrial steam, process heat, and residential heating in Northern China. However, the plan ultimately triggered a natural gas crisis, because there were not enough natural gas supplies during the winter season. The underlying issue was that China lacked adequate seasonal storage facilities to manage the substitution of fuels.

Lesson C4: Wholesale market price variations must be reflected in consumer prices

In the context of China’s energy transformation, where market-oriented reform is embraced as a guiding principle, the risk of allowing parts of the system to operate under market conditions while others remain directly controlled increases the risk of a lack of flexibility and efficiency.

To ensure flexibility and efficiency in China's energy transformation, it is essential to align wholesale market price fluctuations with consumer prices. An example was the 2021 power crisis when coal prices increased while the benchmark price of coal-based power (consumer prices) failed to follow this rise in prices. Not only did this place coal generators under financial pressure, as they could not recover costs from end users, but consumers were shielded from the price signals that reflected the actual cost of producing electricity. To address this distorted pricing mechanism, the national government and NDRC then decided that all coal generators and industrial/commercial consumers must be included in the power market, which is stated in document No.1439 (NDRC, 2021).

6. Chinese and European power producers' approach to the energy transition (examples)

This chapter presents a few examples of Chinese and European power producers' approach to the green transition (see the Annex for a more detailed account).

6.1 Examples of Chinese power producers' approach

China Huaneng Group Co., Ltd.

China Huaneng Group Co., Ltd. is a key state-owned company established with the approval of the State Council. The company is mainly engaged in the following businesses: development, investment, construction, operation and management of power sources; production and sale of power and heat; development, investment, construction, production and sale of businesses and products related to finance, coal, transportation, renewable energy, and environmental protection; industrial investment, operation and management.

The company actively promotes green transformation, adheres to low-carbon and clean energy as its main focus, vigorously promotes structural reforms, and strives to develop three key areas of business: new energy, nuclear power, and hydropower.

The company has launched its first nationwide carbon emission pledge financing business, meeting the financing needs of thermal power enterprises while exploring new paths for revitalising carbon assets. Its other activities include actively adapting to the integrated development of the electricity market under the 'dual carbon' goal, and establishing a green certificate and carbon trading office, achieving coordinated management of green certificate and carbon trading. In 2021, more than 100 of the company's thermal power enterprises completed carbon trading contracts. Meanwhile, its management and operation of carbon assets have achieved significant results.

Datang Group

China Datang Corporation Limited (CDT) is a major state-owned power generation enterprise, its main areas of business including electric power, coal and coal chemical industries, finance, environmental protection, trade and logistics and emerging industries. CDT owns five listed companies, as well as 36 regional subsidiaries and specialised companies.

By the end of 2022, CDT's power generation assets in operation and under construction were widely distributed in 32 provinces all over China, including Hong Kong, as well as in foreign countries and regions such as Myanmar, Cambodia, Laos, Indonesia etc., with assets amounting to CNY 860 billion, and an installed capacity of 172 GW, of which clean energy units account for 42% of the total. CDT has been a Fortune Global 500 company for 13 consecutive years.

CDT actively explores the path of low-carbon development, taking green development as its responsibility, providing carbon management services, researching and developing carbon capture technologies, conducting carbon market transactions, and using smart and effective strategies to promote emission reduction and carbon reduction work. All these activities are underpin Datang's efforts to help achieve carbon peak and carbon neutrality.

CDT is monitoring closely the new electricity market reforms, promoting the integration and mutual promotion of the electricity market and carbon market, and moving forward with low-carbon and high-quality development, while actively carrying out carbon emission trading under the ‘dual carbon’ goal.

6.2 Examples of European power producers’ approach

Ørsted

The Ørsted vision is a world that runs entirely on green energy. Headquartered in Denmark, Ørsted develops, constructs, and operates offshore and onshore wind farms, solar farms, energy storage facilities, renewable hydrogen and green fuels facilities, and bioenergy plants. Ørsted is recognised on the CDP[16] Climate Change A List as a global leader on climate action and was the first energy company in the world to have its science-based net-zero emissions target validated by the Science Based Targets initiative (SBTi). Ørsted employs around 9 000 people. Ørsted's shares are listed on Nasdaq Copenhagen (Orsted). In 2022, the group's revenue was DKK 132.3 billion (EUR 17.8 billion) (Ørsted, 2023).

RWE

This German power producer (responsible for generation of 1 560 TWh/year) wants to phase out coal by 2030. RWE employs around 19 000 people worldwide and has a clear target: to reach net-zero carbon by 2040.

To achieve this, the company has set itself ambitious targets for all activities that cause greenhouse gas emissions.

With an extensive investment and growth strategy, the company intends to expand its powerful green generation capacity to 50 GW internationally by 2030. RWE is investing more than EUR 50 billion gross for this purpose in the 2020s.

RWE’s portfolio is based on offshore and onshore wind, solar, hydropower, hydrogen, batteries, biomass, and gas. RWE Supply & Trading provides tailored energy solutions for large customers. RWE has operations in Europe, North America, and the Asia-Pacific region (RWE, 2023).

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[16] The Carbon Disclosure Project (CDP) is a not-for-profit international charity that runs the global disclosure system for investors, companies, cities, states and regions to manage their environmental impacts.

7. Conclusions

The adoption of the Paris Agreement and the ambitious climate targets set by China and the EU require a major overhaul of energy systems. This transitional stage features a growing share of variable renewable energy (VRE) resources and technological uncertainties, and brings with it new risks and the need for a redefinition of the concept of *energy security*.

The co-existence of the fossil-fuel dominated system of the present and the emerging carbon-neutral system of the future creates tensions between two rather differing operational paradigms.

A detailed understanding is needed of the specific risks surrounding the ongoing transition, including quantitative metrics to assess these risks and measures to mitigate them.

This is the final report in the ECECP project: 'B2.4e Energy Security in the Context of Energy Transition– Lessons and Challenges Within Europe and Within China'. The project was launched on 24 August 2023 and ended in November 2023. The project partners are CEC (China Electricity Council), DEA, and Ea Energy Analyses. The first part of this report explored the concept of energy security in China and the EU in the context of the energy transition. In the second part of the report (WP2), we offer a quantitative assessment of the risks associated with increased dependency on climate and weather patterns, e.g. wind and solar power in a future with a high share of VRE in the power system (EU in 2050 and China in 2060). The authors have achieved this by measuring the degree to which RE-resources will contribute towards maintaining generation adequacy, relative to projected demands.

China's perspective on energy security

China's energy security concerns align with the principles outlined in the 'New Energy Security Strategy,' placing an emphasis the following key points:

- **Enhancing Energy Efficiency:** The first priority is to drive an energy consumption revolution by reducing inefficiencies in energy use.
- **Diversifying Energy Supply:** The second objective is to promote a revolution in energy supply, fostering a diversified supply system.
- **Advancing Energy Technology:** The third aspect focuses on advancing energy technology to facilitate industrial upgrading.
- **Transforming Energy Systems:** The fourth goal involves revolutionizing energy systems, opening up a fast lane for energy development.
- **Global Energy Cooperation:** Finally, there is a commitment to strengthening international cooperation to ensure energy security within an open environment.

The EU's perspective on energy security

The EU's energy security concept underscores cooperation and solidarity among Member States and regional partners. Cross-border cooperation, inter-connections and a functioning electricity market ensure that electricity can flow between Member States and partner countries and that the different countries can rely on each other.

The energy crisis triggered by the conflict in Ukraine has accelerated renewable energy deployment in the EU, driving the bloc to sharply reduce its dependence on Russian natural gas imports. In May 2020, the European Commission proposed the 'RePowerEU Plan', which has three main components: energy conservation, a rise in clean energy and diversification of energy supplies. This strategic response addresses the short- to medium-term energy crisis while accelerating the energy transition to reach the long-term decarbonisation targets.

Transitioning to Net-Zero Carbon: Navigating Energy Security Risks

The report goes on to offer a more global overview of energy security risks during the transition, ranging from fuel dependence risk and electricity system risks to cybersecurity risk and geopolitical risks. Each of the risks highlights the complex challenges and considerations involved in transitioning to a cleaner energy system.

For six risks that are particularly relevant to both China and the EU, suggested mitigation measures are given, as summarised in the table below.

Table 6.1: Key Risks and Mitigation Measures in China and the EU

Risk	Mitigation measures China	Mitigation measures EU
Dependence on imported fuels	Increase cooperation with foreign suppliers. Diversify the import between different exporting countries. Consolidate internal supply chains for the development of synthetic fuels. Commit to a decarbonisation pathway involving renewables.	Continue the strategy of diversifying the import between different exporting countries.
Dependence of clean energy technologies on critical materials	Increase efforts to survey and explore the availability of critical materials in China. Direct investment in overseas sources of critical materials. Expansion of the mid and downstream in the critical materials supply chains. Invest in the development of alternative technologies which reduce or avoid the need for critical raw materials.	Direct investment in overseas sources of critical materials. Expansion of the critical materials supply chain through the establishment of contracts and long-term agreements. Invest in the development of alternative technologies which reduce or avoid the need for critical raw materials.
Inflexible and inefficient demand	Adopt cost reflectiveness in all energy prices. Adopt a decisive initiative to measure and digitise energy consumption	Further adopt cost reflectiveness in all energy prices. Further adopt a decisive initiative to measure and digitise energy consumption while creating

Table 6.1: Key Risks and Mitigation Measures in China and the EU

Risk	Mitigation measures China	Mitigation measures EU
	while creating measures to incentivise consumer awareness. Create incentive mechanisms for retrofit and technology substitution.	measures to incentivise consumer awareness. Create incentive mechanisms for retrofit and technology substitution.
Climate impacts on energy production (renewable and non-renewable)	Invest in power system flexibility e.g. transform coal-fired plants in China to enhance the flexibility for the whole electricity system. Enhance sector coupling. Invest in adequate reserves of climate-resilient firm capacity. Invest in more flexible and market-integrated inter-provincial transmission. Invest in both short-term and seasonal energy storage technologies. Incentivise demand response.	Invest in power system flexibility. Enhance sector coupling. Invest in adequate reserves of climate-resilient firm capacity. Invest in more flexible and market-integrated transmission including new interconnectors between countries. Incentivise demand response.
Uncoordinated technology transition	Develop a phase-in and phase-out plan focusing on specific metrics. Prolong the use of existing energy infrastructure. Model the mid-transition and evaluate intermediate scenarios. Synchronise scaling up green fuels and technologies with scaling down fossil infrastructure.	Develop a phase-in and phase-out plan focusing on specific metrics. Prolong the use of existing energy infrastructure. Model the mid-transition and evaluate intermediate scenarios. Synchronise scaling up green fuels and technologies with scaling down fossil infrastructure.
Insufficient transmission system integration	Integrate the transmission system into the market mechanism, for example through implicit capacity auction in the market coupling mechanism. Integrated generation-transmission planning.	Build new infrastructure/expand existing transmission where profitable (benefits >costs). Adopt socialised cost recovery mechanism in countries where this is not applied.

Table 6.1: Key Risks and Mitigation Measures in China and the EU		
Risk	Mitigation measures China	Mitigation measures EU
	Adopt socialised cost recovery mechanism. More flexible inter-provincial transmission, which can adapt to the seasonal characteristics of resources in different regions. Accelerate the development of energy storage. Expand cross-regional infrastructure to transmit renewable power, pursuing transmission rescheduling, netting supply-demand imbalances and expanding resource-sharing areas.	Adopt CBCA (cross border cost allocation) as a method to encourage cost sharing. Better utilise existing capacity (e.g., dynamic line rating). Integrated generation-transmission planning Accelerate the development of energy storage.

Similarities and disparities between China and the EU in energy security have been identified as follows:

- Both China and the EU are reducing their dependency on imported fuels by prioritising large-scale deployment of renewables like PV and wind, leading to decreased risk over time.
- China holds a global leadership position in technology and critical material supply chains, whereas the EU relies on global trade and long-term agreements. The EU is focusing on critical material recycling to mitigate dependency and enhance environmental sustainability.
- In terms of demand flexibility and efficiency, Europe has implemented energy markets and rolled out smart meters to end-consumers, allowing for better price responsiveness. This mechanism is more developed compared to China.
- Both China and the EU anticipate climate impacts on energy production, regardless of technology choices for carbon neutrality. The risks and mitigation measures are similar.
- The risk of uncoordinated technology transition is comparable in both China and the EU, as are the proposed metrics and mitigation measures.
- The potential barrier of an insufficient transmission system for the green transition, especially for solar and wind, is recognized in both regions. Europe has an established planning regime for power transmission, including sector coupling with natural gas and hydrogen. China's transmission development could be more market-led and efficient with the adoption of a fully-fledged market approach, including a spot market.

Quantitative weather impacts on energy production

In the second section of the report, we consider the complete decarbonised power systems of the EU by 2050 and China by 2060 with a substantial share of VRE. Through a quantitative assessment that examines how VRE resources contribute to generation adequacy amidst changing weather patterns, we gain valuable insights into the associated risks linked to climate and weather conditions. The scenario data for China 2060 is obtained from the CEC and CETO project, while the data for the EU is sourced from ENTSO-E's TYNDP 2050 Global Ambition and Distributed Energy scenarios.

Findings from the quantitative assessment of weather impacts on energy production

- Solar droughts are generally of longer duration in EU countries (where there is a higher seasonal impact), while China is experiencing longer durations of wind energy droughts.
- The analyses reveal that residual load droughts are generally short, lasting less than a day, in both China and the EU, with China experiencing more frequent events due to lower VRE generation coverage in the scenario.
- The main need for flexibility in the VRE-dominated power systems in both the EU and China relates to achieving daily balancing of the power system between hours.
- Regions with a higher proportion of solar PV in VRE generation will generally have greater daily flexibility needs, while regions with a higher share of wind energy will require more flexibility on a weekly basis, aligning with the durations of solar and wind energy droughts.
- Solutions for flexibility needs will vary depending on the timescale, with short-term flexibility achievable using batteries or rapidly adjustable energy sources, while long-term flexibility is better addressed using technologies such as pumped hydro.
- Responsive, flexible energy sources are needed to fill the gaps left by VRE, potentially reducing the need for long-term baseload capacity during periods of low wind or solar generation and high demand.
- A capacity remuneration mechanism could ensure power adequacy in the few hours of peak load, as relying solely on the spot market may not incentivise backup power investment.

Mitigating energy security risks: lessons from the EU and China

Both the EU and China offer valuable insights in the handling of specific energy security threats and managing related risks.

- Lesson E1 underscores the EU's efforts to reduce its reliance on Russia as a primary fossil fuel supplier by advocating for diversified natural gas sources, implementing a joint procurement system (Aggregate EU'),and introducing short-term market correction measures that do not distort the market.
- Lesson E2 emphasises the importance of maintaining a balanced approach between emergency intervention and long-term market reform in response to energy crises, cautioning against excessive interference with liberal market price signals to safeguard the benefits achieved over time, as demonstrated by the EU's introduction of an inframarginal generator market revenue cap to address rising electricity prices and support renewables.
- Lesson C1 stresses the significance of diversifying fuel imports for energy security, highlighting China's successful efforts to obtain oil, gas, coal, and uranium from a variety of international sources while also maintaining a domestic supply.
- Lesson C2 highlights the vital role of diversifying the supply of critical materials for the transformation of China's energy system, highlighting the country's strategic advantage in clean energy technology supply chains.

- Lesson C3 shows that to mitigate risks, it is crucial to avoid an uncoordinated transition of technologies, as it can be a challenge to determine the optimal timing and rate of transition.
- Lesson C4 emphasises that in the context of China's energy transformation, market-oriented reform needs to reflect wholesale market price variations in consumer prices to ensure flexibility and efficiency.

This report has shown that redefining *energy security* is crucial in the context of the energy transition for both the EU and China due to the monumental shift towards renewable and variable energy sources. As these regions aim to decarbonise their energy systems, traditional notions of energy security centred around fossil fuel availability and geopolitical stability no longer suffice. Instead, the emphasis is shifting towards ensuring reliable access to clean energy technologies, critical materials, and a resilient grid infrastructure. Additionally, cooperation, diversification of supply sources, and flexible demand management become paramount when navigating the challenges of an evolving energy landscape.

The quantitative assessment of weather impacts on VRE can assist the strategic placement of renewable sources, storage sizing, and grid design to accommodate weather-induced fluctuations in generation and can support decision-makers in China and the EU to make well-informed choices for investment, integration, and management of VRE resources, ensuring a dependable and secure energy supply during their journey towards net-zero emissions.

8. ANNEX

Annex 1: China's official line on energy security

Chinese Government documents on the security principles of the power system

The year 2035 is defined as China's target year to achieve the status of a 'modernised country'; this is a mid-transition state before reaching the final state of a 'rich, strong, democratic, civilised, harmonious and beautiful modernised powerful country' by mid-century (X. Chen et al., 2023). While this vision includes the economy and society as a whole, environmental sustainability is highlighted throughout on condition that security of energy supply and economic competitiveness are ensured. To ensure security of supply for a growing electricity demand during the transition, the Chinese government has published several general guideline documents that highlight and define the importance of energy security in the power sector (see Table 8.1).

Table 8.1: Overview of Chinese Government Documents on Energy Security

Time	Publisher	Document	Significance for energy security
March 2021	The Central People's Government of the People's Republic of China	*The Outline of the 14th Five-Year Plan for Economic and Social Development and long-range objectives through the year 2035 of the People's Republic of China*	Calls for a management and control system for energy emergencies; increase of baseload reserve capacity
September 2021	Party Central Committee, State Council	*Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy*	Emphasises that decarbonisation must be in balance with energy security
October 2021	State Council	*Action Plan for Carbon Dioxide Peaking Before 2030*	Oil and gas capacity needs to be built first to stabilise the system, before a gradual replacement with new energy[17]
March 2022	NDRC, NEA	*The 14th Five-Year Plan (2021-25) for a Modern Energy System*	Increase of independent power supply and electricity emergency capacities
June 2023	NEA	*Blue Book on the Development of New Power System*	Vision of a new energy system, with coal still playing a security role. A variety of power grid systems exist to ensure safe, stable and efficient operation. Power market is coupled with carbon market

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[17] 'new energy' is here used as mainly renewable energy

In March 2021, the Central People's Government of the People's Republic of China (2021) issued *'The Outline of the 14th Five-Year Plan for Economic and Social Development and long-range objectives through the year 2035 of the People's Republic of China'* (hereafter 'Outline'), specifying the overall government priorities. On the power sector, the Outline stipulates that through the implementation of diversified guaranteed measures and the strengthening of reserves, the generation, supply, storage, and market-based systems will be improved and the capacities for a sustainable and stable energy supply as well as risk management and control will be increased, including capacity expansion of coal as a reserve capacity. A management and control system for energy emergencies is required to ensure the supply of electricity to the main cities and consumers and to better protect the major energy plants and grids.

In September 2021, the Party Central Committee and The State Council issued the 'Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy' (hereafter 'Working Guidance'). The Working Guidance puts forward the principles of exercising nationwide planning, prioritising conservation, leveraging the strengths of the government and the market, coordinating efforts on the domestic and international fronts, and guarding against risks. 'Guarding against risks' refers to efforts to reduce pollution and carbon emissions which must be balanced with the need to ensure the security of energy, industrial chains, supply chains, and food, as well as normal daily life. The Working Guidance makes provision for any economic, financial, and social risks that may arise during the green and low-carbon transformation, to prevent any excessive response and ensure carbon emissions are reduced in a safe and secure way.

In October 2021, the State Council issued *the 'Action Plan for Carbon Dioxide Peaking Before 2030'* (hereafter 'Action Plan'). The Action Plan provides for CO_2 emissions to be safely reduced in a 'steady and orderly manner'. Given that China's energy resources are rich in coal but poor in oil and gas, this Action Plan envisages capacity building before decommissioning, in order to stabilise the energy stock. National energy security and economic development must not be jeopardised, but a gradual replacement with new energy should promote a smooth transition to low-carbon energy. Concrete steps are being taken to ensure China's energy and food security, the safety of industrial and supply chains, and to ensure that citizens can live and work as usual. While the reduction of CO_2 emissions will be pursued progressively, they will be weighed against the various potential risks and hazards to avoid excessive side effects and ensure a safe reduction of CO_2 emissions.

In June 2023, the NEA issued the '*Blue Book on the Development of New Power System'* (hereafter 'Blue Book'). The Blue Book posits four key characteristics in the new power system: safe and efficient, clean and low-carbon, flexible, and intelligent integration. 'Safe and efficient' underlies the construction of new power infrastructure. New energy gradually becomes the main power supply of the system through improvements to ensure reliable support capacity. Coal power is still the 'ballast stone' of power security and bears the 'heavy burden' of basic security. Multi-timescale energy storage operates cooperatively to support the power system to achieve dynamic balance. 'Big power supply, big power grid' and 'distributed energy' are compatible, and a variety of power grid forms coexist, jointly supporting the safe, stable, and efficient operation of the system. The power market, adapted to a high proportion of new energy, is coupled with the carbon market and the energy market to promote the efficient operation of the energy power system.

Policy recommendations

China’s official line on energy security and how this is evolving in context of energy transition is summarised in Chapter 3.4. Several policy recommendations can be derived:

Firstly, strive for stable supply and pricing in relation to China’s domestic fossil energy resources. Fossil energy still counts for the majority of China’s energy supply, i.e., more than 50%. A stable supply and price not only affect social welfare, but also have implications for the sustainable and smooth transition towards net zero.

Secondly, accelerate the construction of a climate-resilient energy infrastructure system. Strengthen the impact and risk assessment of climate change on energy production, transportation, storage, and distribution. Strengthen the protection and emergency dispatch of power transmission and distribution systems under extreme weather and climate events. Strengthen the monitoring and inspection maintenance of power equipment and promote the application of technologies such as energy storage, smart grids, and digitisation. Improve the emergency response plan system and enhance the ability to predict, warn, defend, respond to, and quickly recover safety risks in power infrastructure. Strengthen the normal operation guarantee of energy infrastructure and improve the ability to withstand extreme weather and climate events such as storm surges, high temperatures, and freezing. Through a deep-seated integration of ‘energy + meteorology’ information, the level of energy supply security guarantee will be enhanced.

Thirdly, establish and improve a policy mechanism system that adapts to the energy system and security needs. Build a national unified market system that meets the effective flow of factors, as well as a strong administrative emergency support system, clarify the boundaries between the two, and establish a transition plan to improve the transition between market and administrative mechanisms. Further deepen the reform of electricity policies, strengthen the role of electricity market and price signal regulation, enhance the system's ability to adjust across time and space, increase the effective capacity of power sources, guide users to avoid peak electricity consumption, and ensure the safe operation of the system. Accelerate a unified and coordinated development of policy measures, in areas such as environmental protection, carbon reduction, land use, and safety assurance in accordance with the requirements of system integration and collaborative efficiency.

Fourthly, improve the integration of electrical systems and the integration of different energy systems. Enhance the inter-regional connections from renewable energy rich regions. Improve the flexibility of the system operation that allows two-directional power flow to gain more balancing power from a large-scale expansion. Provide more connections between system planning and market prices, by using price signals in an assessment of grid or generation construction plans.

Government documents on main security objectives of power system

In the following, China’s key governmental documents on energy security are summarised:

In March 2022, the National Development and Reform Commission and the National Energy Administration issued *'The 14th Five-Year Plan (2021-25) for Modern Energy System’* (hereafter called ‘Plan’). The Plan states that independent energy supply capacity will be further enhanced **by 2025**. Key cities, core regions, and important users will have significantly improved their power emergency security capabilities by the same year.

The Blue Book states that **in the period to 2030**, as the ‘ballast stone’ of power security, coal power will be transformed to provide basic support and system regulation power.

Before 2030, the installed capacity and power generation of coal power will still grow moderately and focus on the overall optimisation of the layout of large new energy bases, major load centres, and important grid nodes. The construction of the electricity market will be steadily improved, and by 2030 a unified national electricity market system featuring unified, open, orderly competition, safe, efficient, and sound governance will be fundamentally complete.

Between 2030 and 2045, the Blue Book foresees the focus of new energy development shifting to enhance safe and reliable alternative capabilities and actively promote local consumption and utilisation. Major breakthroughs have been made in large-scale long-term energy storage technology to meet the needs of balanced adjustment over the day. Diversified development of new energy storage technology routes to meet the needs of system power supply security and large-scale new energy consumption.

Between 2045 and 2060, traditional power sources such as coal power have been transformed into system regulatory power sources to provide emergency support and backup capacity. Disruptive technologies such as enhanced dry hot rock power generation and controlled nuclear fusion are expected to achieve breakthroughs and gradually be commercialised. Large power grids with AC and DC interconnection and distributed smart grids that actively balance regional power supply and demand and support comprehensive energy utilisation coexist widely, jointly ensuring safe and reliable power supply.

The Working Guidance states that **by 2060**, China will have fully established a green, low-carbon and circular economy and a clean, low-carbon, safe and efficient energy system.

Government documents on security arrangements for the power system

A)

The Working Guidance advocates accelerating the development of a clean, low-carbon, safe and efficient energy system.

Coal-fired power will be developed in coordination with power supplies and peak shaving capacities, so as to strictly control coal-fired power generation projects. Upgrades and power flexibility retrofitting projects should be accelerated for existing coal power generators. The burning of bulk coal will be gradually phased out before the introduction of a complete ban. Scaled development of unconventional oil and gas resources such as shale gas, coal bed gas, and tight oil and gas will pick up pace. Risk management must be enhanced to ensure a stable and safe energy supply and a smooth transition.

B)

The Blue Book calls for strengthened power supply security, power safety standards, and safety technology innovation.

B1) Strengthen the construction of a supporting system for ensuring power supply

Taking green and security into consideration, actively develop conventional hydropower and nuclear power, build natural gas peaking power plants according to local conditions on the premise of implementing gas sources, promote clean and low-carbon development of coal power, optimise the development layout, and enhance the reliable alternative capacity of new energy by relying on technological innovation.

B2) Strengthen standards research in the field of power safety

Formulate and improve standards for the safe and stable operation and control of power systems. Strengthen research on power information security, meteorological power data security and network security standards. Promote the development of standards in the field of power emergency technology and management, and improve the system's ability to prevent, resist and respond to extreme events, as well as its ability to quickly restore power supplies.

B3) Strengthen innovation in the application of core technologies and major equipment

Clean, safe, and efficient power generation technology and equipment.

In order to ensure the safe, efficient, economic and sustainable development of nuclear power projects, optimise key nuclear power technologies and develop and apply new generation nuclear power, accelerate the application of comprehensive utilisation technologies of nuclear energy, promote the application demonstration of advanced reactor technologies such as high-temperature gas-cooled reactors, fast reactors, modular small reactors and floating reactors at sea, and support research and development of nuclear fusion technology.

Large-scale, high safety energy storage technology equipment.

Focus on long-life, low-cost and high-safety electrochemical energy storage key core technologies, equipment integration optimisation research, development of new energy storage materials, improve the safety of lithium batteries, reduce costs, and press forward with the development of sodium ion batteries, flow batteries and other diversified technology routes. Research and development of on-board power batteries to meet the needs of new power systems and build a load aggregation system for electric vehicles. Vigorously promote the development of compressed air energy storage, flywheel energy storage, gravity energy storage, supercapacitors, hot (cold) energy storage and other technologies to large-scale, high-efficiency and flexible operation, and carry out research and demonstration of key technologies. Breakthroughs have been made in key technologies such as proton exchange membrane and high-temperature solid oxide electrolytic hydrogen production suitable for renewable energy electrolytic water hydrogen production. Research and development and promotion of key technologies are now needed, such as hydrogen storage and transportation/filling, fuel cell equipment and system integration, and the development of pure hydrogen gas generator sets.

Safe and stable operation technology for the power system.

Research and development of power system simulation analysis and safe and efficient operation technology, including large-scale new energy access to the power system dynamic process simulation technology, improve the simulation as the core of the new power system analysis cognitive ability. Research has been carried out on broadband oscillation analysis and suppression technology, key technologies for DC power grid system operation, high-proportion new energy and high-proportion power electronic equipment connected to the power grid stable operation control, and other technologies to improve the safe and stable operation of the power system. Promote research on online prevention and control technologies for power system security and stability risks, construction technologies for a new integrated defense system for power systems, identification, and prevention of unconventional security risks for power systems and improve power system security and stability defense and emergency response capabilities.

C)

The Plan advocates improvements to the safety level of power system operation and strengthened emergency safety controls.

C1) Improve operational safety

Give full play to the supporting regulatory role of coal power.

Make overall plans to ensure power supply and reduce pollution and carbon, make rational plans for construction of advanced coal power plants according to development needs, maintain the reasonable margin necessary for safe and stable operation of the system, accelerate the transformation of coal power plants from the main power source to the basic support and system regulatory power source that provides auxiliary services such as reliable capacity and peak and frequency regulation, and give full play to the emergency peak regulation capacity of existing coal power units. Promote the construction of supportive and adjustable power supplies in an orderly manner.

Maintain the security of energy infrastructure.

Strengthen the security protection and protection of major energy facilities, improve the joint prevention and control mechanism, focus on ensuring the safety of nuclear power plants, hydropower stations, key transformer substations, major converter stations, major transmission corridors, and large-scale energy and chemical projects, and strengthen the protection of oil and gas pipelines. Comprehensively strengthen the safety management of nuclear power, implement the strictest safety standards and the strictest supervision, always put the principle of "safety first, quality first" throughout all aspects of nuclear power construction, operation and decommissioning, implement the safety responsibility of the whole chain to people, and continue to improve the safety level of units under operation to ensure that nothing is wrong.

C2) Strengthen emergency safety control

Strengthen power security in key regions

In accordance with the principle of "key guarantee, local tenacity, and rapid recovery", with the focus on municipalities directly under the Central Government, provincial capitals, and cities independently planned, the power emergency supply and accident recovery capacity will be improved. Coordinate the optimization of local power grid structure and the construction of interconnected transmission channels, reasonably improve the construction standards of related lines and substations in core areas and important users and strengthen the mutual support of power grids under accident conditions. Promote the construction of local emergency support power supplies, encourage qualified important users to develop distributed power supplies and microgrids, improve the configuration of users' emergency power supplies, and coordinate the construction of urban black start power supplies and public emergency mobile power supplies.

Raise the level of energy cybersecurity control

Improve the security prevention and control system of the power monitoring system and strengthen the security protection capacity of key information infrastructure in the power and oil and gas industries. Promote the application of the Beidou Global Navigation Satellite System in the energy industry. Strengthen research on key technologies for cybersecurity, promote the establishment of cybersecurity situation awareness and monitoring and early warning platforms for the energy industry and enterprises, and improve risk analysis, research, and early warning capabilities.

Strengthen management of potential risks and emergency management.

Investigate and control hidden dangers in important facilities and key links, strengthen equipment monitoring, inspection and maintenance, and improve the ability to forecast, provide early warning, and offer defense and response to safety risks such as earthquakes and geological disasters, extreme weather, and fire. Promote the construction of electric power emergency systems, strengthen the main responsibility of local governments and enterprises, and establish electric power safety emergency command platforms, training and exercise bases, emergency rescue teams and expert databases. Improve the emergency planning system, formulate emergency response plans, carry out real-combat emergency drills, and improve the ability to respond quickly. Establish and improve construction standards for electrochemical energy storage and hydrogen energy, strengthen key supervision, and improve product safety and emergency response capabilities. Appropriately raise security and defense standards in the energy sector and improve systems and standards for the protection of power facilities, security and anti-terrorism prevention.

Annex 2: Major power producers’ energy transition in China

Chapter 6 of the report presents a few examples of Chinese and European power producers’ approach to the green transition. At the invitation of the report authors, Chinese power producers have provided a more comprehensive description of their approach. Minimal edits have been made.

Huaneng Group

China Huaneng Group Co., Ltd. is a key state-owned company established with the approval of the State Council.

With registered capital of CNY 34.9 billion, the company is mainly engaged in the following businesses: development, investment, construction, operation and management of power sources; production and sale of power and heat; development, investment, construction, production, and sale of businesses and products related to finance, coal, transportation, renewable energy, and environmental protection; industrial investment, operation and management.

The company actively promotes green transformation, adheres to low-carbon and clean energy as its main focus, vigorously promotes structural adjustment, and strives to create three key areas of business: new energy, nuclear power, and hydropower. The ‘two lines’ and ‘two modernisations’ strategies have entered a harvest period. The ‘North Line’: This is the first multi-energy complementary green comprehensive energy base of tens of millions of kilowatts in China. Construction has begun on the Longdong Energy Base and a development pattern of large-scale bases is developing steadily. The ‘East Line’: This is a comprehensive process model integrating investment, construction, and operation and maintenance of offshore wind power bases.

The company is constantly working to achieve top-level construction of carbon neutrality work. It has established the Huaneng Carbon Neutrality Research Institute, which conducts basic research on carbon neutrality strategic direction, evolution laws, and technological innovation. It is the first carbon neutrality research institute among central enterprises in the power industry. The company actively conducts research on the ‘dual carbon’ path, participates in major consulting projects and research projects with the Chinese Academy of Engineering and the State-owned Assets Supervision and Administration Commission, and has formulated two technical standards. In 2021, the company's ‘Large Power Group Carbon Asset Management Platform Based on Big Data Technology’ was recognised for its solutions to promote the integration of industrialisation and application innovation in the power industry.

The company has launched its first nationwide carbon emission pledge financing business, meeting the financing needs of thermal power enterprises while exploring new paths for revitalising carbon assets. The business is actively adapting to the integrated development of the electricity market under the ‘dual carbon’ goal, establishing a green certificate and carbon trading office, achieving coordinated management of green certificate and carbon trading, saving over 2 million tons of quota resources, and reducing carbon compliance costs by CNY 16.35 million. In 2021, more than 100 thermal power enterprises of the company completed carbon trading contracts 14 days in advance, sold 5.24 million tons of carbon quotas, and generated an additional profit of CNY 23.74 million. Its management and operation of carbon assets achieved significant results.

Datang Group

Founded on 29 December 2002, China Datang Corporation Limited (CDT) is a large-scale state-owned power generation enterprise, its main businesses covering electric power, coal & coal chemical industry, finance, environmental protection, trade & logistics and emerging industries. CDT owns five listed companies, and 36 regional subsidiaries and specialised companies.

By the end of 2022, CDT’s power generation assets in operation and under construction were widely distributed in 32 provinces all over China, including Hong Kong as well as in foreign countries and regions such as Myanmar, Cambodia, Laos, Indonesia etc., with assets amounting to CNY 860 billion, total installed capacity of 172 GW, of which clean energy units accounted for 42%. CDT has been a Fortune Global 500 company for 13 consecutive years.

CDT actively explores the path of low-carbon development, making green development its responsibility, providing carbon management services, researching and developing carbon capture technologies, conducting carbon market transactions, and using smart and effective strategies to promote emission reduction and carbon reduction work, contributing to Datang's efforts to help achieve carbon peak and carbon neutrality.

CDT is taking an active role in the construction of the carbon trading market, providing new development ideas and high-quality management services in green consulting, low-carbon asset operation, green finance, low-carbon investment, etc., creating a green, low-carbon, and high-quality development ecosystem and circle of friends for consultation, joint construction, and sharing, contributing to China's achievement of the ‘dual carbon’ goal and the construction of a beautiful China.

CDT focuses on key regions and key links, continuously exploring the domestic market, energetically expanding the green consulting business market outside the group, actively integrating into the construction of a new development pattern, adhering to open cooperation, and working with local governments in the Beijing Tianjin Hebei region and Hubei, Shenzhen, etc. to jointly build a carbon trading market. The company is actively involved in the construction of the Hainan Free Trade Zone (Port), provides consulting services for the Hainan Carbon Emission Trading Centre, and is assisting in construction of a national-level external carbon asset trading platform with international emission reduction trading at its core. It is carrying out a ‘dual carbon’ strategic cooperation with Chongqing to promote the construction of the Western Green Resources Exchange.

CDT is closely following the new situation of electricity market reform, promoting the integration and mutual promotion of the electricity market and carbon market, and moving forward with low-carbon and high-quality development, and engages in carbon emission trading under the ‘dual carbon’ goal. In 2022, the company took the initiative to leverage its professional advantages and participated in multiple official meetings with the Ministry of Health and Environment, China Electricity Council, actively reflecting the opinions of market entities. It regularly participates in discussions organised by the Ministry of Health and Environment on the Implementation Plan for Setting and Allocating the Total Amount of National Carbon Emission Trading Quotas for 2021-22, and has conducted research on the national carbon market (electricity) prosperity index project.

Huadian Group

China Huadian Corporation Ltd (CHD) is one of five state-owned sole proprietorship power generation corporations set up at the end of 2002 under the national reform of the electricity system. Its main business activities include power generation, heat production and supply, development of primary energy supplies relating to electricity such as coal and relevant technical services. It has grown from an electric power generator to a comprehensive energy group with rising position in the industry. In 2023, the corporation was included in the Fortune Global 500 for the tenth year in a row with its ranking rising by 18 places to No. 352 from the previous year.

CHD is working to optimise the power generation structure and build a new type of power system with new energy at its core. CHD is focused on building a clean, low-carbon, safe and efficient energy system, fully implementing the new energy security strategy of ‘Four Revolutions, One Cooperation’, advocating for the green transformation, sustainable development of hydropower, vigorously promoting the ‘base based, large-scale’ development of wind and solar power, and working towards the orderly development of natural gas power generation.

CHD’s priority is to tap the potential of coal and promote development of the coal industry to achieve carbon reductions. CHD actively undertakes the dual tasks of energy supply guarantee and green transformation, working on coal mining, strengthening low-carbon mining in coal mines, carrying out energy-saving technological transformation of mining equipment, and continuously reducing energy consumption intensity in coal mine development and utilisation. At the same time, it is striving to accelerate the construction of green mines, exploring the implementation of ecological value-added mining, and the development path of near zero or negative emissions in mines, its aim being to contribute to the energy revolution, build an energy powerhouse, and achieve the dual carbon’ goals as scheduled.

CHD is working to accelerate technological breakthroughs and cultivate new driving forces for low-carbon industrial development. It plans to research and develop key technologies such as carbon monitoring, capture and utilisation, biomass utilisation, and solid waste blending. It vigorously promotes the research and application of energy storage technologies, is rapidly developing the research and demonstration of key hydrogen energy technologies, and is focused on creating a comprehensive energy service business with CHD characteristics that is ‘clean, friendly, multi energy joint supply, and smart and efficient’. At the same time, the company intends to comprehensively deepen the construction of digital CHD and fully leverage the value of energy data.

CHD is also focused on integrating internal and external forces to promote green and sustainable development. CHD focuses on top-level design, issues featured in the 14th Five-Year Plan for development, helped to draft the 13th Five-Year Plan for carbon emissions white paper and carbon peak action plan, and is also giving input into refinements of the key indicators and key tasks of the carbon peak action plan according to the requirements of carbon emissions ‘dual control’. Relevant indicators are included in the annual performance evaluation of directly affiliated units; The company established the first directly affiliated unit level carbon asset intensive operation platform of a central enterprise, and promotes the intensive management of carbon asset carbon trading; It has established a ‘1+5+N’ carbon emission management system for the group company, issued the ‘Greenhouse Gas Emission Management Measures’ for the group, established a greenhouse gas management service agency, and is working constantly to improve the carbon emission management system. In the energy field, CHD has drawn up industry standards such as the ‘Technical Specification for Continuous Monitoring of Carbon Dioxide Emissions from Thermal Power Plants’ and ‘Quantitative Methods and Evaluation Standards for Carbon Emissions from Wind Power Projects Throughout their Life Cycle’, and it is working to offer its experience, set an example, and set a benchmark on the ‘dual carbon’ path, creating a ‘CHD brand’ for low-carbon solutions.

CHN Energy Investment Group

CHN Energy Investment Group (CHN Energy) was formally established on 28 November 2017, following the merger of China Guodian Corporation and Shenhua Group. It is a key state-owned energy enterprise (SOE) directly administered by the central government, playing a pioneering role in the restructuring of SOEs, the reform of state-owned capital investment, the efforts to build a top-notch energy company with global competitiveness, and the reform of SOE corporate governance.

The company provides products and services of whole industrial chains including coal, electric power, transportation and chemical industry. With operations distributed in 31 provinces, autonomous regions and municipalities across China, as well as more than 10 countries and regions including the United States and Canada, CHN Energy is the world’s largest company in coal mining, thermal power, wind power and coal-to-liquids industry. It has been rated as Grade A in 2021 business performance assessment on leaders of central enterprises and Grade A in the 2019-2021 term assessment. In 2022, it was ranked 85th on the Fortune Global 500 list, up 16 places from the previous year.

CHN Energy is actively participating in the construction of a new type of power system with new energy as the main fuel source, providing diversified, rapid, large-scale, cost-effective, and scientific development of renewable energy, and has established an energy industry system that covers clean and efficient coal power, gas power, wind energy, solar energy, biomass energy, tidal energy, geothermal energy, and hydrogen energy. The company is a major contributor in terms of its knowledge and corporate strength to the national endeavour to achieve the ‘dual carbon’ goals.

The company is pressing ahead with rapid development of large base construction projects. The group fully leverages its multi-industry advantages, responds to national strategies, actively arranges and develops tens of millions of kilowatt level large base projects such as wind, solar, thermal storage integration, and water and solar integration, focusing on promoting the construction of green, low-carbon, and circular industrial chains, and injecting green energy into achieving the ‘dual carbon’ target.

CHN Energy is a leader in the wind power industry. While developing wind and solar power base projects, it gives equal emphasis to onshore, offshore, and overseas projects, continues to maintain the leading advantage in wind power, accelerates the promotion of a number of key offshore wind power projects, and promotes the rolling and continuous development of the wind power industry.

The company is developing its PV activities very rapidly. The group has issued guidance on accelerating the development of the PV industry, adapting to local conditions, leveraging strengths and avoiding weaknesses, and promoting multiple industries to comprehensively expand PV development. While actively promoting the construction of centralised PV power generation bases, the group is also actively developing PV projects in coal mine subsidence areas and reclamation areas and developing distributed PV projects.

CHN Energy is also involved in innovating and developing the hydrogen energy industry. The group is accelerating construction of a ‘green hydrogen supply chain’ and a ‘hydrogen alliance service chain’ system, deepening the national green hydrogen supply layout of ‘"East West North South Middle’, promoting the construction of wind and solar energy hydrogen storage and other base projects, and injecting strong impetus into the ecological prosperity of the hydrogen energy industry.

A key target is to strengthen carbon asset management. Various professional service companies of CHN Energy are accelerating the creation of original technology and modern industrial chain technology, continuously enhancing the main business capability of financial services. With the launch and gradual improvement of the national carbon emission trading market, the group is an active participant in developing the market and strengthening carbon asset management.

State Power Investment Corporation Limited

State Power Investment Corporation Limited (SPIC) is one of China's five power generation groups, with businesses covering centralised power and heat generation, consumer-side integrated smart energy, green P2X, power-related and supporting sectors, and asset-light businesses. SPIC owns all generation types including PV, wind, nuclear, hydro, coal, gas and biomass, with its PV power capacity ranking first in the world. Ranking 260th among the Fortune Global 500, SPIC is committed to becoming a world-class clean energy enterprise that is globally competitive.

SPIC attaches great importance to global climate change issues and actively explores and strives to implement innovative practices. It carries out carbon emission control work, and issued the ‘Carbon Emission Management Measures’, to help improve the construction of carbon emission systems. It is exploring CCUS technologies, and pressing ahead with innovations that will achieve the large-scale reduction of greenhouse gases. It is strengthening carbon asset management, while innovating and enhancing the green and low-carbon value of clean energy.

SPIC is focused on developing carbon reduction technologies. It is doing this by leverage its own technological, management, and financial advantages to promote innovative research and development of carbon reduction technologies and the application of key demonstration projects. On 27 December 2022, the coal-fired flue gas CCUS innovation demonstration project of Shanghai Power Changxing Island Power Plant's 100 000-ton coal-fired gas turbine was put into operation. This project features the carbon dioxide capture technology of SPIC Yuanda Environmental Protection, which has independent intellectual property rights. The pre-treated flue gas enters the carbon capture and absorption system and comes into contact with the absorbent. The CO_2 in the flue gas is absorbed, with absorption efficiency reaching over 90%. Once in full operation, the project has the potential to reduce CO_2 emissions by 90 000 tons per year, reduce CO_2 emissions from shipping by about 10 400 tons, and achieve a total reduction of 100 000 tons per year, equivalent to planting 5.56 million trees on the island.

SPIC is also applying carbon reduction tools. By organically integrating the carbon market, green certificate market, and electricity market, it aims to connect the electricity carbon industry chain. The company wants to give full play to the advantages of leading clean energy enterprises, and promote the construction of a power carbon emission rights and green financial system centered on new energy. The company is also exploring the possibility of linking green oil and gas trading, carbon trading, and the Chinese yuan, and use ‘new energy + finance’ to help enhance the position of the Chinese yuan in the international financial market, continuously amplifying new momentum for green development. In July 2022, SPIC became one of the first members of the Hong Kong International Carbon Market Committee and the only energy enterprise. In October 2023, SPIC successfully participated in the first batch of transactions in the Hong Kong international carbon market, completed the first order listing and the first Chinese yuan green equity transaction in the Hong Kong international carbon market, opening up domestic and foreign trading fund circulation channels for the first time.

China Three Gorges Corporation

The China Three Gorges Project Corporation was founded on 27 September 1993 to construct the Three Gorges Project and develop the Yangtze River, with the approval of the State Council. On 27 September 2009, it was renamed the China Three Gorges Corporation (CTG). CTG positions itself as a clean energy group focusing on large-scale hydropower development and operation. Its main businesses cover construction, international investment and contracting, development of wind power and solar energy among other renewable energies, comprehensive development and utilisation of water resources, as well as providing relevant professional technical services. After more than 20 years of rapid growth, CTG has become the largest hydropower development enterprise worldwide and the biggest clean energy group in China.

CTG has established a mechanism of ‘Party and government responsibility, one position dual responsibility’ for ecological environment protection, and has set up a leading group to work on ‘carbon peak and carbon neutrality’. It is working on predictions for carbon peaking, and has drawn up the ‘Carbon Peak Action Plan of China Three Gorges Group Co., Ltd.’, as well as completing carbon peak planning for the 14th Five-Year Plan and the 15th Five-Year Plan, clarifying carbon peak goals, the roadmap, key tasks, and major projects.

By focusing on key tasks such as optimising industrial structure and layout, and promoting green and low-carbon energy transformation, CTG will continue to enhance the competitiveness, creativity, control, and influence of green and low-carbon development, fully leverage the advantages of clean energy as the main business, expand the effective supply of clean energy, help improve the green and low-carbon energy transformation, promote the construction of China's new energy system, and actively and steadily promote carbon peaking work.

CTG has formulated the ‘Work Plan for Orderly Promotion of Green Power Consumption, and has sold a total of 9 378 domestic affordable green certificates and 3.5893 million international green certificates, as well as completing almost 1.997 billion kWh of green power trading. It has sold around 376 200 tons of international voluntary emission reduction products (VCS), and approximately 345 800 tons of domestic Chongqing voluntary emission reduction products (CQCER). The value of green bonds issued (including sustainable development linked bonds) reached CNY 57.4 billion, marking the largest scale of issuance by domestic non-financial enterprises. As of the end of 2022, the balance of green credit reached a historic high at over CNY 250 billion.

The company’s thermal power enterprises actively carry out operational work, maintenance, technical transformation, and combustion adjustment optimisation of environmental protection governance facilities to ensure ultra-low emissions of sulphur dioxide, nitrogen oxides, and smoke during normal operation of the units. All thermal power units in Hubei Energy meet the requirements for pollutant discharge permits. The company runs energy-saving publicity weeks and national low-carbon day activities, promotes low-carbon living, and endeavours to ensure that the concept of energy conservation and environmental protection is deeply rooted in people's hearts.

The company has established a carbon-neutral intellectual property alliance and has won approval for a national carbon-neutral intellectual property operation centre. CTG intends to deepen the research and development of cutting-edge clean energy technologies such as hydrogen energy and new energy storage, create the most comprehensive technical testing laboratory for energy storage in China, and establish a comprehensive demonstration project for hydrogen energy production, storage, transportation, addition, and use. It has held themed seminars on ‘International Cooperation and Emission Reduction Mechanisms and Carbon Asset Development of Overseas Projects of Chinese Enterprises’ and ‘Policy Interpretation and Future Prospects for Green Power Trading’.

China General Nuclear Power Corporation

The preliminary work of Daya Bay Nuclear Power Plant in Guangdong province began in 1979, and China General Nuclear Power Corporation (CGN) was founded in 1994. CGN is focused on the development of clean energies such as nuclear power, nuclear fuel, wind power, and solar power. With over 30 years’ experience in R&D and operation of nuclear power projects, CGN has 39 000 employees worldwide. CGN is now one of the largest nuclear power operators in China and the largest nuclear power construction company in the world.

In accordance with the relevant requirements of the State owned Assets Supervision and Administration Commission of the State Council, such as the ‘Guiding Opinions on Promoting the High Quality Development of Central Enterprises’ and ‘Doing a Good Job in Carbon Peak and Carbon Neutrality’, and in response to the situation on the ground, CGN has formulated the ‘Group Carbon Peak and Carbon Neutrality Action Plan’ and ‘Group Energy Conservation and Carbon Reduction Action Plan’, clarifying its basic principles of ‘overall deployment, classified implementation, conservation priority, source carbon reduction, innovation driven, and technology led’ energy-saving and carbon reduction actions. The company has vowed to organise and promote the key work of energy conservation and carbon reduction, and focus on energy conservation and carbon reduction in key areas.

Centred on the ‘dual carbon’ strategy, CGN aims to build a clean energy development pattern where nuclear energy and new energy go hand in hand, and actively reduce its own operational carbon emissions. Developing clean energy to help reduce carbon emissions in society, CGN stands ready to seize new opportunities for clean energy development, and develop plans for green, low-carbon, and high-quality development from both strategic and tactical perspectives, promoting the low-carbon transformation of the energy structure in China and worldwide. CGN wishes to develop its green operations and reduce carbon emissions. It has responded actively to national policies related to energy conservation and emission reduction, focusing on strengthening energy consumption management in various production units, conducting a full process diagnosis and evaluation of energy efficiency and usage management in the case of old factories, stations, and equipment, and formulating energy-saving transformation implementation plans for ‘one factory, one policy’. CGN is accelerating the provision and deployment of energy-saving products for energy facilities in living and office areas. Every individual constituent of CGN actively promotes energy conservation and consumption reduction through multiple practical measures that follow its central tenet: ‘to reduce pollution, reduce carbon emissions, and enhance efficiency’.

Annex 3: The Introduction of Scenarios and Data Collection (CEC)

The introduction of scenarios and data collection

The data introducing the current status have been selected from public sources. The data relating to future development has in general been assumed for the purpose of energy security analysis and does not represent a generation plan.

1. VRE data

Provincial VRE data is based on the **'China Electric Power Statistical Yearbook 2022'** and **'The 2023 Annual Report of Power Industry development in China'** published by CEC. The assumptions relating to VRE annual growth relate to the following periods: 2022-30 with 40 GW wind and 70 GW solar; 2031-45 with 40 GW wind and 75 GW solar; 2046-60 with 40 GW wind and 80 GW solar.

The basis for calculations is the VRE shares of each province in the country in 2022, the VRE shares in the central and eastern provinces are taken to be slightly higher - 3.5% higher for solar and 2.6% higher for wind, while the shares of western and northern provinces are reduced accordingly.

2. Offshore wind data

The data for this report has been taken from the following website:

https://news.bjx.com.cn/html/20220719/1242197.shtml.

The Chinese Wind Energy Association presented a report on the off shore wind capacity in related coastal provinces, while GEIDCO published a study report 'China's 2030 Power Development Plan and 2060 Outlook' which suggested the potential for of 159 GW offshore wind. Based on the shares of offshore wind in coastal provinces in 2021, the 159 GW are assumed to be similarly distributed.

(http://www.chinasmartgrid.com.cn/news/20210319/638159.shtmlchinasmartgrid.com.cn)

3. Demand forecast

The demand forecast data was selected from the published paper, 'Carbon Peak and Carbon Neutrality Path for China's Power Industry', from the journal 'Engineering Sciences', Issue 6, 2021.

http://www.engineering.org.cn/ch/journal/SSCAE/archive?volumeId=1316

The paper projected 15 700 TWh of demand in 2060. Based on the demand shares of each province in the country in 2022, the western and northern provinces have been given a slightly higher share (2.93%), and the shares of the central and eastern provinces are reduced accordingly.

4. Hydroelectricity data

CEC has not published monthly capacity factor data of hydroelectricity. The data of annual capacity factors in 10 provinces with more than 10 GW during the years 2016-22 are taken from **'China Electric Power Statistical Yearbook 2022'** and **'The 2023 Annual Report of Power Industry Development in China'**.

9. Abbreviations

ACER – (EU) Agency for the Cooperation of Energy Regulators

CBA – Cost benefit analysis

CBAM – Carbon Border Adjustment Mechanism

CBCA – Cross-Border Cost Allocation

CCS – Carbon, Capture, Utilisation and Storage

CCUS – Carbon, Capture and Storage

CIS - Commonwealth of Independent States

CONE – Cost of new energy

CSP – Concentrated solar power

CWEA - Chinese Wind Energy Association

DSF – Demand side flexibility

DSR – Demand side response

EENS – Expected Energy Not Served

ETS – Emissions Trading System

EV - Electric Vehicle

IEA – International Energy Agency

IRA – (US) Inflation Reduction Act

ITRE – European Parliament’s Committee on Industry, Research and Energy

LCOE - Levelised Cost of Energy

LNG – Liquified natural gas

LOLE – Loss of Load Expectancy

LNG - Liquefied natural gas

MOSES – (IEA) Model of short-term Energy Security

NDRC – (China) National Development and Reform Commission

NEA – (China) National Energy Administration

P2X - Power-to-X

PGM – Platinum group metals

PV – Photovoltaic

SoS – Security of Supply

TTF - Title Transfer Facility

TYNDP – (ENTSO) Ten Year Network Development Plan

UNFCCC – United Nations Framework Convention on Climate Change

VOLL – Value of Lost Load

VRE – Variable renewable energy

WEO – (IEA) World Energy Outlook

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Note: All Figures shown without a source are based on research undertaken by the authors of this report.

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