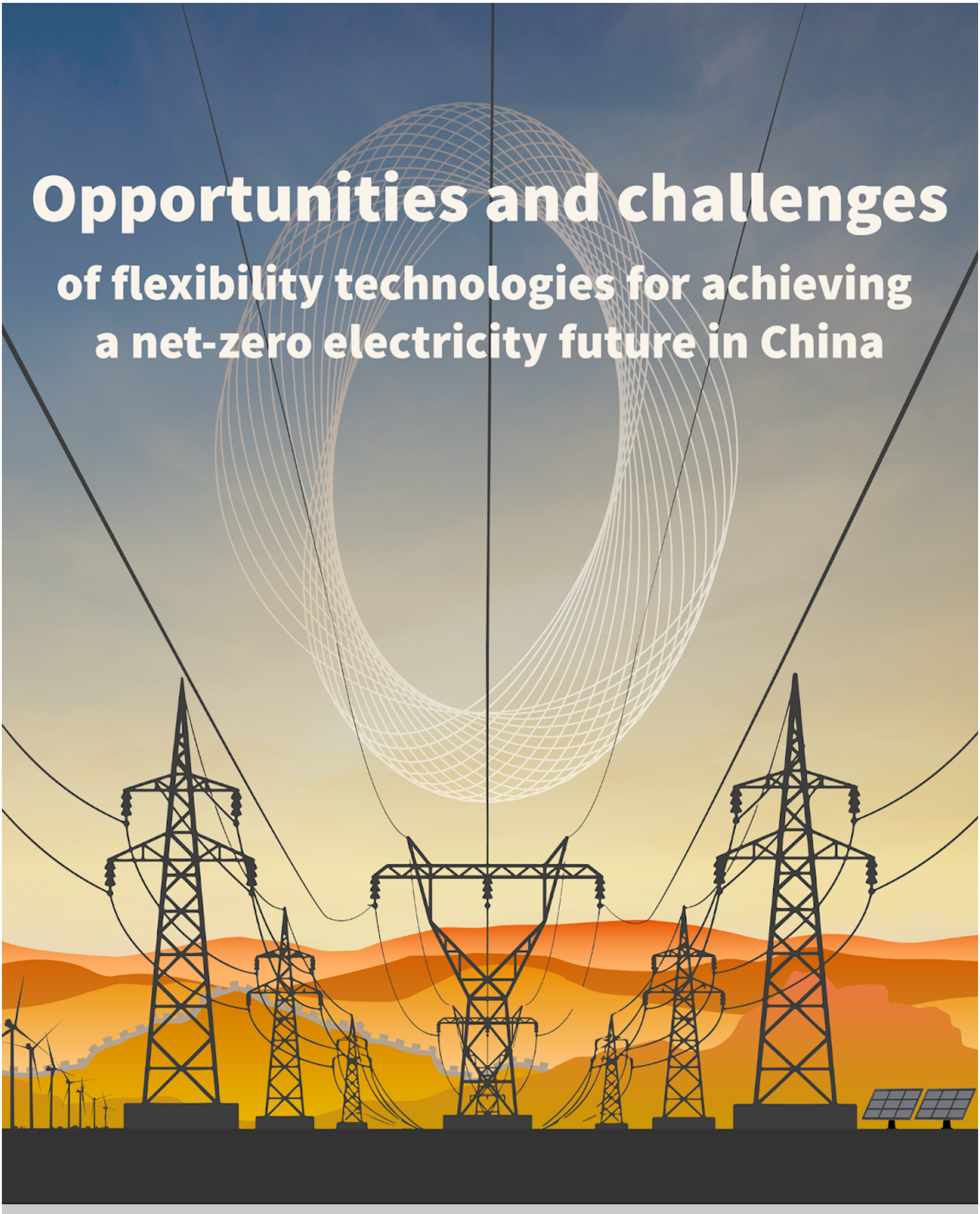
Opportunities and challenges

of flexibility technologies for achieving a net-zero electricity future in China



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Opportunities and challenges of flexibility technologies for achieving a net-zero electricity future in China

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About CREA

The Centre for Research on Energy and Clean Air (CREA) is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions, to air pollution. CREA uses scientific data, research and evidence to support the efforts of governments, companies and campaigning organisations worldwide in their efforts to move towards clean energy and clean air. We believe that effective research and communication are the key to successful policies, investment decisions and advocacy efforts. CREA was founded in 2019 in Helsinki, Finland and has staff in several European and Asian countries.

About ISETS

The International Society for Energy Transition Studies (ISETS) is an independent, non-profit, global membership organization based in Australia that facilitates a just, equitable and inclusive transition of energy and relevant sectors towards a sustainable low-carbon future with consideration of economic development, social equity, and environmental stewardship through international partnerships.

Contents

Executive summary

China has experienced significant growth in renewable electricity generation in recent years and is expected to see even more as the country works towards achieving its dual carbon goals of peaking emissions before 2030 and reaching carbon neutrality before 2060. Accommodating these new variable renewable sources will require significant investment and changes to the broader power system. There is also a sense of urgency in implementing these systemic changes due to the need to manage changing demand profiles with higher peak and more volatile consumer demand. Fluctuating demand for electricity is mainly caused by the more frequent occurrence of extreme weather conditions (e.g., heatwaves) and the increased use of heating and air conditioning in the household sector.

Changes happening in China's power system not only involve building more renewable energy projects. Change also entails reconfiguring the whole electricity system necessary to support the uptake of renewable generation. System flexibility, the ability of a system to manage variations in electricity demand and supply reliably and cost-effectively, stands at the core of this system reconfiguration. This raises the questions: what technical solutions are available for improving the flexibility of the power system in China; what are the main issues (techno-economic, market and regulatory) that may affect their uptake; and, more importantly, what should be done to address them?

The main objective of this report is to develop some insights into these questions by delving into the viewpoints and perspectives held by key energy stakeholders in China. These insights will enable the identification of differing interests and cross-cutting issues that need to be addressed, to facilitate consensus building and ensure a rapid uptake of various flexibility technologies. The method adopted in this report is a combination of literature review and expert survey. The main points arising from the analysis conducted in the report are presented below.

- There exists a range of technologies that can help Chinese system operators to manage abrupt changes in electricity supply and demand. Some key technologies include coal power flexibilisation, pumped hydro, battery storage, green hydrogen, thermal energy storage, and demand-side response.
- Gas-fired power plants, although widely considered as a reliable and dispatchable

complement to support the integration of large renewable energy into the grids, are only expected to play a limited role in China. This is mainly due to concerns about high and volatile gas prices and import dependence, exacerbated by geopolitical complexities and domestic instabilities of gas-exporting countries.

- Deeper power connectivity, facilitated by harmonised regulatory and market arrangements across different provinces of China, would enable better cross-provincial balancing and capacity sharing, allowing more effective sharing of complementary renewable resources that are often distributed unevenly across the country. However, the implementation of necessary market and regulatory reforms remains challenging, implying that power connectivity cannot be considered an immediate solution to support further expansion of renewable generation in China.

Technical feasibility

Many flexibility technologies are still emerging at the research stage (conceptualisation), are in development (proof of concept through demonstration projects), or are at an early market introduction stage. Out of the technologies covered in this report, coal power flexibilisation, pumped hydro, lithium ion batteries and demand response (including vehicle-to-grid) are already mature technologies, some of which are ready for wider adoption.

At a systems-wide level, flexibility technologies could help improve the overall efficiency of the electricity system by enabling higher levels of renewable energy penetration, as well as contributing to lower carbon dioxide (CO_2) and pollutant emissions.

For coal power, plant level flexibilisation could affect fuel efficiency (and therefore potential higher CO_2 emissions) and lead to increased wear and tear of equipment, caused by frequent increase (‘ramping’) and decrease in demand to provide load following services.

Engineering complexity and access to core patents are not seen as a major concern for flexibility technologies, given China’s engineering and research capacity and capabilities, especially for coal power flexibilisation, pumped hydro, battery storage, and demand-side response.

For periods of long-duration seasonal variations that affect renewable sources, the study considers coal power flexibilisation and green hydrogen as potentially viable solutions.

Safety concerns, however, could limit the scale-up of hydrogen supply capacity in the near future. Another issue associated with fossil-based hydrogen, not mentioned by participants in the survey, is the uncertainty around carbon capture and storage (CCS). CCS is required to reduce the carbon footprint of hydrogen production in a net-zero future. Other options are being explored by researchers, for example, thermal storage technologies like molten-salt storage have also demonstrated the potential to provide long-duration storage solutions via pilot projects.

Cleanliness

In the expert survey, demand-side response, vehicle-to-grid, pumped hydro, and green hydrogen were seen as preferable technologies from the perspective of greenhouse gas (GHG) and air pollutant emissions.

Economic viability

Many flexibility technologies are considered by experts to lack economic viability in China's current power system, with a payback period of more than five years. The reasons behind this vary by technology: pumped hydro is impacted by long lead times and high development costs (for example, costs involved in land acquisition and infrastructure construction); rising critical mineral prices for battery storage; and high costs of electrolysers or fossil reformation equipped with carbon capture, utilisation, and storage (CCUS) for hydrogen.

Enabling infrastructure

One issue currently holding back the widespread use of hydrogen is the lack of infrastructure to transport, distribute, store and dispense hydrogen as a fuel for stationary uses.

For pumped hydro, some ideal sites are found in areas far away from the existing road and transmission infrastructure, making their development expensive.

Demand-side technologies, including demand-side response, virtual power plant, and vehicle-to-grid, have emerged as attractive options for managing short- to medium-term variations in electricity supply and demand. Their wider adoption, however, could be affected by the lack of necessary infrastructure, such as smart meters, sensors, communication technology and the Internet of Things. The development of this infrastructure could also be affected by the lack of standardisation and protocols for metering and information technologies, and public concern about data security and privacy, among other issues.

Market and regulatory arrangements
Promoting the uptake of various flexibility technologies requires regulatory and market reforms to better articulate the demand for system flexibility arising from higher levels of renewable energy penetration.

The findings of this report highlight that for innovative flexibility technologies to be deployed at scale, several technical, economic, infrastructure, regulatory, and market issues need to be addressed. By implication, this also suggests that a flexible, clean, and modern electricity system, capable of accommodating large outputs from variable renewable energy sources, can only be developed if several layers of mutually interacting and unpredictably reinforcing factors, such as technology, economics, policy, and social aspects, move forward simultaneously in a concerted way.

Some key aspects for policymakers to consider for guiding the process of addressing flexibility within the wider energy transition are summarised below.

Coal power flexibilisation demotes coal power to a supportive role, generating less power from coal and creating space for more clean energy in the grid. It is an immediately actionable step towards addressing flexibility shortfalls in China's electricity system. It serves as a leverage point for necessary market and regulatory reforms that would pave the way for the wider adoption of clean flexibility technologies. Clean flexibility technologies, such as battery storage, green hydrogen, and thermal energy storage, are not yet mature enough to be deployed at the scale considered essential for supporting further expansion of variable renewable energy generation in China. The policy of the current energy five-year plan of demoting coal power to play a supportive role in providing ancillary and capacity (not baseload) services, therefore, provides a short-term measure. During the Two Sessions in 2022, the National Energy Administration (NEA) indicated that, 'in principle', it will not permit the construction of new coal power projects exclusively for electricity generation, but stated the possibility of building 'supportive units' of a 'certain scale' to ensure supply sufficiency and provide flexibility services to moderate-variable renewable generation.

Facilitating this change in the role of coal power will require the implementation of necessary market and regulatory reforms to create more effective mechanisms for procuring ancillary and capacity services. These mechanisms, once established, would also enable the integration of clean flexibility technologies into the system when they become more mature.

Deeper power connectivity could unlock substantial additional flexibility from existing capacity, but implementation remains a challenge. Power connectivity envisages the creation of a fully interconnected national electricity system that allows cross-provincial and cross-regional sharing of surplus and reserve capacity, facilitated by grid interconnection, and coordinated market operation. Deeper power connectivity could allow more effective sharing of complementary renewable resources (especially, hydro, wind and solar) that are distributed unevenly across the country, thereby reducing the need for expensive reserve and backup capacity. It could also provide increased access to a variety of supply- and demand-side options for managing variations in renewable generation.

In recognition of the importance of power connectivity, the central government has recently signalled its intention to accelerate the construction of a unified national power market. Despite this, how to deepen market reform in practice remains an issue, especially considering the experience of electricity market reform in China. After nearly three decades of efforts, the utilization of cross-provincial and cross-regional power connectivity in China remains rather low, limited to a few centrally planned initiatives.

Innovation is critical to prepare clean flexibility technologies for wider adoption, where increased R&D support is important but, in isolation, will not bring needed results. The generation, diffusion, and utilisation of novel technologies are not only shaped by technology-focused ‘hardware’ innovation processes. Indeed, they are also influenced by the dynamic interplay of actors (e.g., utility companies, private investors, consumers, and research institutes) and broader institutional structures, such as laws and regulations, market mechanisms, policy frameworks, and technical norms.

A more systemic approach is therefore needed to support innovation in flexibility technologies. This approach comprises: demand pull via market reform and indicative planning; technology push by addressing blocking factors for bringing innovation to the market; and policy learning and adaptation.

Improving the flexibility of the Chinese power system requires an all-of-government approach, closely coordinating climate and supply security imperatives with other cross-cutting issues. For example, retrofitting coal-fired power plants to enable a shift in their use from baseload capacity to supportive capacity means lower capacity utilisation rates and hence less coal burnt for power generation and less coal production needed. This could, in turn, affect economic development in some coal-dependent regions. Another example is electricity affordability, as the upfront costs of system reconfiguration could put upwards pressure on the regulator to raise electricity prices, which may be viewed by the government as a potential threat to people’s living standards.

执行摘要

过去十年里，中国电力行业的清洁转型加速推进，可再生能源发电量实现了大幅增长。中国正在力争实现2030年前碳达峰、2060年前碳中和的“双碳”目标，这意味着这场能源转型很可能在未来几年内进一步深化。因此，可再生能源，如风能、太阳能和水电，将逐渐取代煤电，在中国的电力系统占据核心地位——这一过程在当下讨论中通常被称为清洁电力转型。

清洁电力转型不仅意味着建设更多的可再生能源项目，还需要对整个电力系统进行必要的重新配置，以实现可再生电力消纳。系统灵活性，即一个系统在合理成本下可靠地管理电力供给与需求波动的能力，是实现这场系统重置过程的关键。考虑到中国电力系统在诞生之初并非是围绕可再生能源波动性大的特性而规划建立的，现有的电力系统设计难以适应可再生能源大规模发电时维持动态平衡的需求，推动系统变革的必要性就更为突出。中国并非唯一面对转型考验的国家，但中国所需推动转型的规模量级远大于其他国家。

随着电力转型的深化，中国需要对其电力系统进行大量投资，尤其需投资灵活性技术。对此，有以下问题需要解答：在中国，有哪些技术解决方案可以用于提高电力系统的灵活性？在技术经济、市场和监管等方面，采用这些灵活性技术的主要面临什么问题？以及更为重要的一点，应该如何解决这些问题？

有鉴于此，本报告的主要目的是通过深入了解中国主要能源从业者的观点，对以上问题提出深度观察。报告采用了文献综述和专家访谈相结合的研究方法，部分关键结论提供如下。

- 目前有一系列技术可以帮助中国的系统运营部门管理电力供应与需求上的急剧变化。其中，一些关键技术包括煤电灵活性改造、抽水蓄能、电池储能、氢能、热能储存和需求侧响应。
- 尽管燃气电厂在可靠性和可调度层面上被公认为是能够支持可再生能源实现大规模并网的技术，但由于中国的天然气依赖进口，叠加地缘政治复杂性以及天然气出口国的内政不稳定性等考量因素后，它在中国的作用和前景被视为是有限的。
- 中国不同省份之间的监管协调和市场机制理顺后，更深层次的电力互联将有助于推动省与省之间的电力平衡和互补，从而使得全国各地分布不均匀却可以相互补充的可再生能源资源更有效地共享。不过，实施必要的监管和市场改革仍

然具有挑战性，这也意味着电力互联无法成为扩大可再生能源发电的直接解药。

技术可行性

一些灵活性技术——煤电、抽水蓄能和锂离子电池——已经成熟，可以被广泛采用。而其他技术或处于研究（概念化）、开发（通过示范项目来验证概念）的阶段，或处于市场引入的早期阶段。

考虑到中国在工程和研究能力上的优势，工程复杂性与获得核心专利的突破能力并不被认为是灵活性技术的主要阻碍，尤其是煤电、抽水蓄能、电池储能以及需求侧响应等技术。

通过提高可再生能源的渗透率，同时减少二氧化碳和污染物排放，灵活性技术有助于提升电力系统的整体效率。与此同时，由于需要更频繁的操作来提供负荷跟踪服务，煤电灵活性也可能影响其自身的燃料效率，导致设备部件的磨损增加。

调研结果显示，煤电和氢能能够为可再生能源长时间、季节性波动的特性提供可行的解决方案。不过，安全问题可能会限制氢气供应在短期内得到进一步扩大的前景。研究人员正在探索其他选择，例如包括熔盐储能在内的热能存储技术等，也通过试点项目展示了其提供长期储能解决方案的潜力。

清洁性

从控制温室气体和污染物排放的角度来看，参与访谈的专家认为需求侧响应、车联网、抽水蓄能和电解制氢是可取的技术。

经济可行性

参与访谈的专家认为，除煤电与需求侧响应技术外，灵活性技术的经济可行性普遍较低，投资回报期通常超过5年。其中，可能的影响因素包括抽水蓄能耗时久、开发成本高（如征地和基础设施建设涉及的成本），电池储能所需的关键矿产品价格上涨，以及电解槽或化石能源重整制氢并配备CCUS的高成本。

基础设施

目前阻碍氢气得到广泛使用的一个问题在于缺乏基础设施来运输、分发、储存和分配氢气，因此限制了氢气作为固定用途燃料的作用。

对于抽水蓄能而言，一些理想的选址地点通常位于远离现有道路和输电基础设施的区域，意味着开发成本高昂。

需求侧技术，包括需求侧响应、虚拟电厂、和车联网已经成为管理中短期电力供需波动的选项中有吸引力的重要选择。不过，如智能电表、传感器、通信技术和物联网等必要基础设施的缺乏，可能会影响这些技术得到广泛采用。这类基础设施的发展也可能受到当前计量与ICT技术缺乏标准化与章程协议、公众担心数据安全与隐私等情况的影响。

市场与监管安排

市场与监管层面需要推进改革，更清楚阐明因提高可再生能源渗透率而产生的系统灵活性需求，从而推动各类灵活性技术的采用。

综上，本研究表明，为了推动创新灵活性技术的大规模部署，还需解决若干技术、经济、基础设施、监管和市场层面的问题。这也意味着，只有上述相互影响的多个层面在共同协调发展的情况下，才能建立一个足够适应可再生能源波动特性的灵活、清洁且现代的电力系统。为了推进这一转变，政策制定者可以考虑以下关键点。

将煤电调整为提供支持性服务的角色是解决中国电力系统僵化问题的一个抓手。煤电灵活性能够减少煤炭发电量，为清洁能源在电网中创造更多空间，不仅有助于进一步推进必要的市场改革，也能够为将来更广泛地采用清洁灵活性技术铺平道路。目前，电池储能、绿氢和热能储存等清洁灵活性技术尚不成熟，还无法大规模部署以支持中国进一步扩大可再生能源发电的规模。因此，一个有吸引力的短期解决方案是，让煤电主要提供辅助和容量服务，而非作为基荷电源，特别是考虑到改造现有煤电厂以提供系统灵活性通常需要不到3个月的时间，而建造一个抽水蓄能电站则需要5至6年的时间。监管与市场层面应有一些针对性的精确调整，以促进煤电角色的转变，并让其他灵活性技术在日臻成熟时有机会得到使用。

进一步深化电力互联可以释放现有电力容量中大量的额外灵活性，但这一点实施起来并不容易。电力互联所设想的是创建一个互联互通的全国性电力系统，允许跨省，跨区域传输冗余和备用电力，通过电网互联和电力市场进行协调。进一步深化电力互联可以让全国非均匀分布的可再生能源（尤其是水能、风能和太阳能）实现更有效的互补，减少对昂贵的备用容量的需求。在供给侧和需求侧上，它也为管理可再生能源发电量波动提供了更多选择。鉴于电力互联的重要性，中国政府近期也释放了加快建设全国统一电力市场的信号。尽管如此，考虑到中国电力市场改革的过往经验，如何在实践中持续推进市场改革的深化仍然是一个问题。开启电力市场改革近三十年后，中国跨省与跨区域的电力互联依然处于相当低的水平，目前仅有少数由中央层面规划的项目。

创新对于清洁灵活性技术的广泛采用而言至关重要，增加研发支持是重要的，但仅有这一点并不会带来所需要的结果。事实上，决定新技术的产生、传播和使用的，不仅包括作为技术核心的 “硬件 ”创新过程，也包括参与者（如公用事业公司、私人投资者、消费者和研究机构）和更广泛的制度结构（如法律法规、市场机制、政策框架和技术规范）之间的动态作用和相互影响。

支持灵活性技术的创新需要一个更为系统性的方法。这一方法包括以下要素： 1）通过市场改革和指示性规划拉动需求；2）通过解决市场创新的阻碍因素来推动技术发展；3）学习并适应政策。

提高中国电力系统灵活性需要政府部门“一盘棋”，密切协调气候、电力供应安全要务与其他相关问题之间的关系。例如，对燃煤电厂进行改造，使其从基荷电源转变为辅助性电源，能够降低其利用率，从而减少为了发电而燃烧的煤炭。这反过来会影响一些煤炭依赖度较高地区的经济发展和就业问题，政策制定者应当在考量中确保本地的公正转型。另一个例子是电力的可负担性，由于重塑系统的成本可能会带来提高电价的压力，因此政府可能会将此视为影响人民生活水平的不利因素。

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1. Introduction

As the world's largest carbon emitter, China has demonstrated its determination to tackle climate change by announcing its dual carbon reduction goals: to achieve peak emissions before 2030 and to attain carbon neutrality before 2060. Energy use is the most significant contributor to CO_2 emissions. However, there is a gap between China's energy and emissions trends due to the fast growth rate of total energy consumption. Resolving this issue requires a combination of increased energy efficiency measures, a shift in the economic growth model, or an even larger scale of clean energy investment than projected in the transition scenarios, together with better-managed energy systems[1]. China's government has highlighted energy efficiency and non-fossil fuel consumption as the 'main objectives' for the top-level Implementation Plan for Carbon Dioxide Peaking and Carbon Neutrality[2] and ordered the acceleration of planning and construction of a 'modern energy system'.

China's power generation sector has been in the throes of a clean revolution over the past decade, with exceptional growth in renewable generation. Between 2010 and 2021, renewable generation in China has grown at an average annual rate of 19.2%, from about 740 TWh in 2010[3] to 2,300 TWh in 2021[4]. Of this growth, about 60% (930 TWh) is from wind and solar power, and this increase in wind and solar power is comparable to Japan's total electricity generated in 2020. The same period also saw hydro generation doubling from about 690 TWh in 2010[3] to 1,340 TWh in 2021[4].

China broke new records in 2022 by adding 125 GW of solar and wind capacity (87 GW solar and 38 GW wind). The added solar and wind generation equals 2% of China's electricity demand, meaning that added wind and solar power covered half of the demand growth of

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[2] Central Committee of the Communist Party of China, State Council (2021). Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy. https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html.

[3] China Electricity Council (2013). 2010年电力工业统计基本数据一览表. https://cec.org.cn/detail/index.html?3-126868.

[4] China Electricity Council (2022). 2021年电力行业基本数据一览表. https://www.cec.org.cn/detail/index.html?3-311093.

3.6%[5]. According to CREA's research, clean energy growth is likely to accelerate because 165 GW of new wind and solar capacity is targeted for installation during 2023 (data indicating if the projects are on track for 2023 were not available at the time of going to press), and bidding for new wind turbine supply contracts reached 100 GW in 2022.

As a result, renewable energies, such as wind, solar, and hydropower, are positioned to gradually replace coal power to occupy a central place in China's electricity system, a process referred to as the clean power transition. Wind and solar are highly weather dependent. Hydropower is dispatchable on short time scales but much of China's hydro is seasonally variable due to the strong seasonality of rainfall and small reservoir size. Hence, the clean power transition process is not just about building more clean power projects. It also requires the whole power system to be reconfigured to accommodate a changing generation mix.

System flexibility is the ability of a power system to reliably manage a high degree of uncertainty and variations in electricity demand and supply in a cost-effective manner, from ensuring instantaneous stability of the power system to supporting long-term security of supply[6], and is central to system reconfiguration. The need for such a systemic change is clear considering that when China's electricity system was built it was not designed to accommodate large outputs from variable renewable energy sources or the current or expected level of demand variability that need to be balanced out flexibly. While China is not alone in facing this challenge, it is handling a transition of far greater scale than other countries.

As the country's electricity transition deepens, it needs to invest heavily in its power system, especially in flexibility technologies. This raises the questions: what technical solutions are available for improving the flexibility of the power system in China; what are the main issues (techno-economic, market and regulatory) that may affect their uptake; and, more importantly, what should be done to address them?

The main objective of this report is to develop some insights into these questions by delving into the viewpoints and perspectives held by key energy stakeholders in China.

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[5] Myllyvirta, L., Yu, A., Champenois, F., Zhang, X. (2023). China permits two new coal power plants per week in 2022.
https://energyandcleanair.org/publication/china-permits-two-new-coal-power-plants-per-week-in-2022/.

[6] IEA (2019). Status of Power System Transformation 2019 - Power system flexibility. https://www.iea.org/reports/status-of-power-system-transformation-2019.

These insights will enable the identification of differing interests and cross-cutting issues that need to be addressed to facilitate consensus building and ensure rapid uptake of various flexibility technologies. The method adopted in this report is a combination of literature review and expert survey.

2. Flexibility technologies: An overview

This section provides an overview of various flexibility technologies as conceptual background to the questions explored in this report.

It is worth noting that, after consulting experts in the energy field in China, some power generation technologies, such as biomass firing, biomass cofiring and gas firing, are not considered in this report, mainly due to their low share in China's energy mix and limited future prospects in China.

By the end of 2022, the installed capacity of biomass power generation accumulated to 41 GW[7], accounting for 1.6% of China's total power generation installations (2560 GW[8]). The main constraint for large-scale implementation of biomass-based power generation is the sustainability of raw biomass resources, particularly in terms of the cost and environmental impact of the biomass supply chain[9].

The main concern about gas power arises from the challenges of accessing sufficient and affordable gas supply. The marginal cost of gas power consuming contracted pipeline gas is around 0.65 yuan ($0.10) per KWh, whereas the marginal cost of coal power is only about 0.5 yuan/kWh ($0.07/kWh) and 0.3 yuan/kWh ($0.04/kWh) for those using spot coal and contracted coal, respectively. The nascent power market did not help, either. In China's most developed province, Guangdong, which has 30% of China's installed gas power capacity, spot power tariffs paid to gas power plants in May 2022 dipped below the marginal cost[10]. State-owned utilities are becoming increasingly cautious about deploying future gas power projects due to the harsh financial penalties imposed by the State-Owned Assets Supervision and Administration Commission on operational projects that suffer losses. This explains why, despite rapid development in recent years as the country seeks to reduce air pollution and carbon emissions, China had only 109 GW of installed gas

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[7] Beijixing (2023) 2022年生物质发电运行情况简介！ https://huanbao.bjx.com.cn/news/20230216/1289133.shtml.

[8] NEA (2023) 国家能源局发布2022年全国电力工业统计数据. http://www.nea.gov.cn/2023-01/18/c_1310691509.htm.

[9] Zhang, X.; Meloni, S. (2020) Technology Developments in the cofiring of biomass. https://www.sustainable-carbon.org/report/technology-developments-in-cofiring-biomass-ccc-305/

[10] BNEF (2022). Rising gas prices threaten China's gas power ambitions. Available at https://www.bloomberg.com/professional/blog/rising-gas-prices-threaten-chinas-gas-power-ambitions/.

capacity as of May 2022[11]. In 2021, gas accounted for only 3.2% of power generation[12].

2.1 Coal power

A rapid and deep cut in coal use is urgently needed. If the annual CO_2 emissions between 2020–2030 stayed, on average, at the same level as 2019, in its Synthesis Report for the Sixth Assessment Report, the IPCC projected that CO_2 emissions from existing fossil fuel infrastructure without additional abatement would exceed the remaining carbon budget for 1.5°C[13]. In the past decade, the main contributors to the global growth in emissions were a growing energy demand and an increase in the share of coal in the global fuel mix[14]. Coal power needs to fall even more quickly than overall coal use, given the important role of electrification in decarbonising other sectors, such as transport, buildings and industry[1].

Flexibilisation is one approach to phasing out coal power, where coal power plants will be demoted to playing a supportive role by providing short- and mid-term ancillary and balancing services and longer duration backup support to the grids. This role is essential for enabling higher levels of renewable energy penetration while maintaining the reliability and security of electricity supply in China[15,16,17].

The operation of coal-fired power plants is subject to their technical capability, which typically involves the minimum load capacity at which a specific generator can operate, the rate at which power output can be adjusted (the ramp rate), start-up and shutdown times, and constraints on how often a generator can be cycled (minimum up/down times as well

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[11] BNEF (2022). Rising gas prices threaten China's gas power ambitions. Available at https://www.bloomberg.com/professional/blog/rising-gas-prices-threaten-chinas-gas-power-ambitions/

[12] BP (2022). Statistical Review of World Energy 2022. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[13] IPCC (2023) AR6 Synthesis Report. Climate Change 2023. https://www.ipcc.ch/report/ar6/syr/.

[14] IPCC (2015). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/wg3/.

[15] Shrimali, G. (2021). Managing power system flexibility in India via coal plants. *Energy Policy,* 150, 112061.

[16] Dong, Y., Jiang, X., Liang, Z., Yuan, J. (2018). Coal power flexibility, energy efficiency and pollutant emissions implications in China: A plant-level analysis based on case units. *Resources, Conservation and Recycling*, 134, 184-195.

[17] Tampubolon, A.P.; Tumiwa, F.; Simamora, P.; Godron, P. (2020). Understanding flexibility of thermal power plants. https://iesr.or.id/v2/publikasi_file/Understanding-flexibility-of-thermal-power-plants.pdf.

as numbers of start-ups)[18]. Enhancing the flexibility of coal-fired power plants, therefore, requires broadening the technical boundary for stable operation, such as lower minimum load capacity, and higher demand increase (ramping) rates. This often involves physical modifications to the boiler and other parts of the power plant (e.g., pulverisers, turbines, rotors, and condenser), as well as changes to operational practices, such as forced cooling, pressure part management (e.g., more frequent review of pressure components), and temperature monitoring to reduce damage to boilers[19].

2.2 Energy storage

Energy storage refers to a process of converting electrical power into a form that can be stored and converted when it is needed[20]. In terms of the form of energy storage, three broad groups of energy storage technologies can be identified:

- electrochemical: battery, hydrogen,
- mechanical: such as pumped hydro, and
- thermal: sensible heat storage, latent storage[21,22].

This section looks at the mainstream energy storage technologies – battery, pumped hydro and hydrogen – that fall into the first two groups. Thermal storage is discussed in Section 2.4.

2.2.1 Battery

Battery storage is a technology that enables power system operators, electric utilities and end-users to store electrical power in the form of chemical energy and discharge it later to provide load relief and balancing services (sub-hourly, hourly and daily) when needed. Table 1 provides further details about applications of battery storage in the power system. Compared with pumped hydro, the main advantages of battery storage are its

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[18] Deloitte (2019). Assessing the flexibility of coal-fired power plants for the integration of renewable energy in Germany. https://www2.deloitte.com/afrique/fr/pages/fusions-acquisitions/articles/assessing-flexibility-coal-fired-power-plants.html.

[19] Cochran, J., Lew, D., Kumar, N. (2013). Flexible Coal: Evolution from Baseload to Peaking Plant (Brochure) (No. NREL/BR-6A20-60575). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[20] McLarnon, F. R., Cairns, E. J. (1989). Energy storage. *Annual Review of Energy*, 14(1), 241-271.

[21] Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19(3), 291-312.

[22] Kousksou, T., Bruel, P., Jamil, A., El Rhafiki, T., Zeraouli, Y. (2014). Energy storage: Applications and challenges. *Solar Energy Materials and Solar Cells*, 120, 59-80.

geographical and sizing adaptability. It can be deployed closer to the location where additional power system flexibility is needed and can be easily scaled according to energy storage needs[23].

Table 1 – Main applications of battery storage in the power system[24]

Application	Description	Duration of service provision
Primary frequency response	Very fast response to unpredictable variations in demand and generation	Seconds
Regulation	Fast response to random, unpredictable variations in demand and generation	Minutes to hours
Contingency spinning	Fast response to a contingency such as a generator failure	Minutes to hours
Ramping/load following	Follow longer-term (hourly) changes in electricity demand	Minutes to hours
Black-start	Unit brought online to start system after a system-wide failure (blackout)	Hours

Several battery chemistries are available for energy storage in the power system, including lithium-ion, lead-acid, sodium-ion, and flow batteries[22]. As costs continue to fall, battery storage installations have seen strong growth in recent years, largely driven by the application of lithium-ion batteries to address short-term variations in renewable generation[25]. Among lithium batteries, lithium iron phosphate batteries are the most preferable choice for grid-scale storage due to their lower costs and good energy density. More energy-dense chemistries for lithium-ion batteries, such as nickel-cobalt-aluminium and nickel-manganese-cobalt, are more popular for home energy storage where space is limited. For applications with longer storage durations, flow batteries, also known as redox flow batteries, have attracted increased attention from energy industry[26].

Battery storage is expected to play an important part in facilitating the global transition

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[23] IRENA (2019). Utility-scale batteries: Innovation landscape brief. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf.

[24] Bowen, T., Chernyakhovskiy, I., Denholm, P. (2019). Grid-scale battery storage, Denver. https://www.nrel.gov/docs/fy19osti/74426.pdf.

[25] Pavarini, C. (2019). Battery storage is (almost) ready to play the flexibility game. https://www.iea.org/commentaries/battery-storage-is-almost-ready-to-play-the-flexibility-game.

[26] Schoenfisch, M., Dasgupta, A., Kamiya, G (2022) Grid-scale storage. https://www.iea.org/reports/grid-scale-storage.

towards a clean electricity future. To achieve a net-zero energy supply by 2050, grid-scale battery storage capacity will need to expand substantially from 16 GW in 2021 to 680 GW in 2030, according to the International Energy Agency (IEA)[26].

2.2.2 Pumped hydro

Pumped hydro is a form of technically proven utility-scale energy storage[27]. This hydroelectric system comprises one upper and one lower reservoir (closed-loop system), or one upper reservoir and a river, sea, lake or other body of water as a lower reservoir (open-loop system)[28]. It works by pumping the water stored in the lower reservoir into the upper reservoir. Like a conventional hydropower plant, the water stored in the upper reservoir can be released to pass through a turbine on its path back to the lower reservoir to produce electricity (see Figure 1 for a simplified illustration). It can be used to manage daily balancing by providing inertia and ancillary services (e.g., voltage and frequency control) to the grids[29]. It can also help address longer duration variations in renewable generation such as hours to weeks[30,31].

Studies published within the past five years suggest huge potential for scaling up global pumped hydro capacity to support the uptake of renewable generation. Based on the application of the geographical information system (GIS) model, one study identified 616,000 potential sites across the world for closed-loop pumped hydro with a combined storage capacity of 23,000 TWh. This is roughly equivalent to total global electricity generation in 2020, implying sufficient storage capacity to support large fractions of variable renewable generation in electricity networks[32]. In a similar study, the global potential for pumped hydro storage is estimated to be around 17,300 TWh with costs lower than USD 50/MWh[31]. Prompted by the need for greater grid flexibility, global pumped hydro

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[27] Koohi-Fayegh, S., Rosen, M. A. (2020). A review of energy storage types, applications and recent developments. *Journal of Energy Storage*, 27, 101047.

[28] Ali, S., Stewart, R. A., Sahin, O. (2021). Drivers and barriers to the deployment of pumped hydro energy storage applications: Systematic literature review. *Cleaner Engineering and Technology*, 5, 100281.

[29] Makarov, Y. V., Reshetov, V. I., Stroev, V. A., Voropai, N. I. (2005, June). Blackouts in North America and Europe: analysis and generalization. In 2005 IEEE Russia Power Tech (pp. 1-7). IEEE.

[30] Kear, G., Chapman, R. (2013). 'Reserving judgement': Perceptions of pumped hydro and utility-scale batteries for electricity storage and reserve generation in New Zealand. *Renewable Energy*, 57, 249-261.

[31] Hunt, J. D., Byers, E., Wada, Y., and others (2020). Global resource potential of seasonal pumped hydropower storage for energy and water storage. *Nature Communications*, 11(1), 947.

[32] Stocks, M., Stocks, R., Lu, B., Cheng, C., Blakers, A. (2021). Global atlas of closed-loop pumped hydro energy storage. *Joule*, 5(1), 270-284.

capacity is expected to increase by almost 50% by 2030. Over 60% of this capacity expansion will take place in China, according to the International Hydropower Association (IHA)[33].

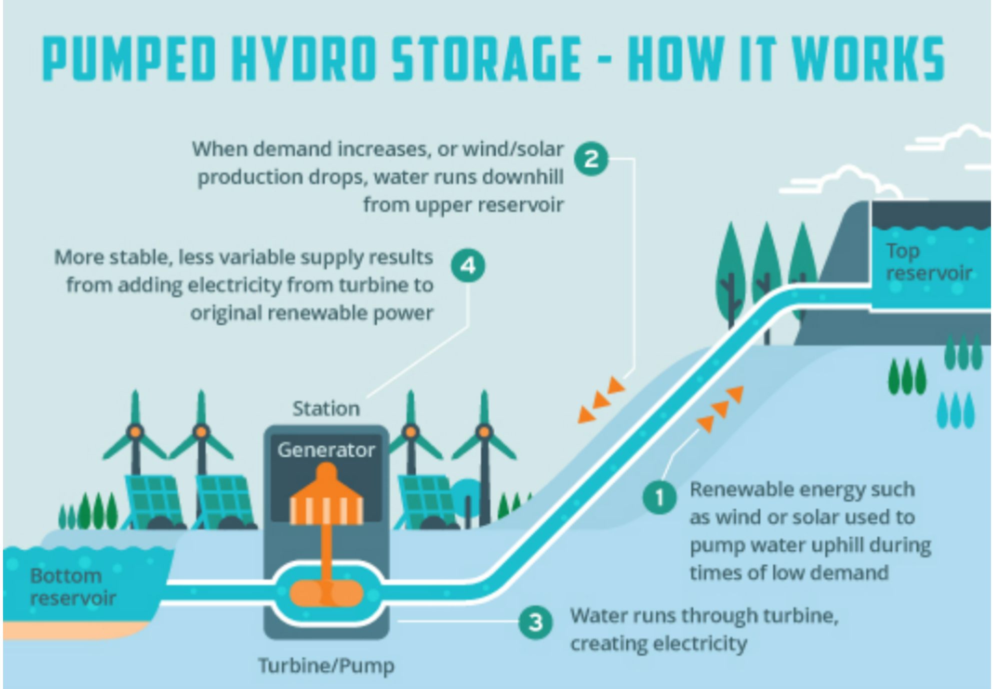

Figure 1 – A schematic showing pumped hydro storage[34]

2.2.3 Hydrogen

Hydrogen, an abundant element, is found in water and hydrocarbons, such as natural gas, coal, and oil[35,36]. It is typically in molecular form (H_2) but can also be condensed to liquid at low temperatures[36]. Hydrogen can be produced from fossil fuels through gasification or steam methane reformation, as well as through electrolysis using electricity (see Figure 2).

Depending on production methods, hydrogen can be classified as *grey*, *blue*, or *green*[37]. Fossil-based hydrogen is either *grey* with no carbon capture, utilisation, and storage

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[33] IHA (2018). The world's water battery: Pumped hydropower storage and the clean energy transition. https://assets-global.website-files.com/5f749e4b9399c80b5e421384/5fa80177d7fd2673249b3471_the_worlds_water_battery_-_pumped_storage_and_the_clean_energy_transition_2_1.pdf.

[34] ARENA (2017). What is pumped hydro and how does it work? https://arena.gov.au/blog/what-is-pumped-hydro-and-how-does-it-work/.

[35] Dawood, F., Anda, M., Shafiullah, G. M. (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy*, 45(7), 3847-3869.

[36] Joshi, M., Chernyakhovskiy, I., Chung, M. (2022). Hydrogen 101: Frequently Asked Questions About Hydrogen for Decarbonization (No. NREL/TP-6A40-82554). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[37] van Renssen, S. (2020). The hydrogen solution? *Nature Climate Change*, 10(9), 799-801.

(CCUS), or *blue* with CCUS. *Green* hydrogen, sometimes also referred to as clean hydrogen, is produced by using electricity generated by renewable energy, such as solar and wind power[37]. According to the IEA , global hydrogen production is currently dominated by fossil fuels: 62% from gas, 19% from coal and 18% as a by-product of oil refining[38].

Hydrogen is widely used in industrial operations, such as oil refining, ammonia and methanol production, and steel manufacturing. Its application is also growing in other sectors, especially in transport, buildings, and power generation[38,39]. In the power sector, hydrogen has gained traction in recent years, mainly because it enables storage of large quantities of clean energy for addressing peak demand and seasonal variations in renewable generation[40]. Clean hydrogen generated from electrolysis using excess renewable electricity during peak production hours can be then used to generate electricity by a combustion engine or a fuel cell when needed.

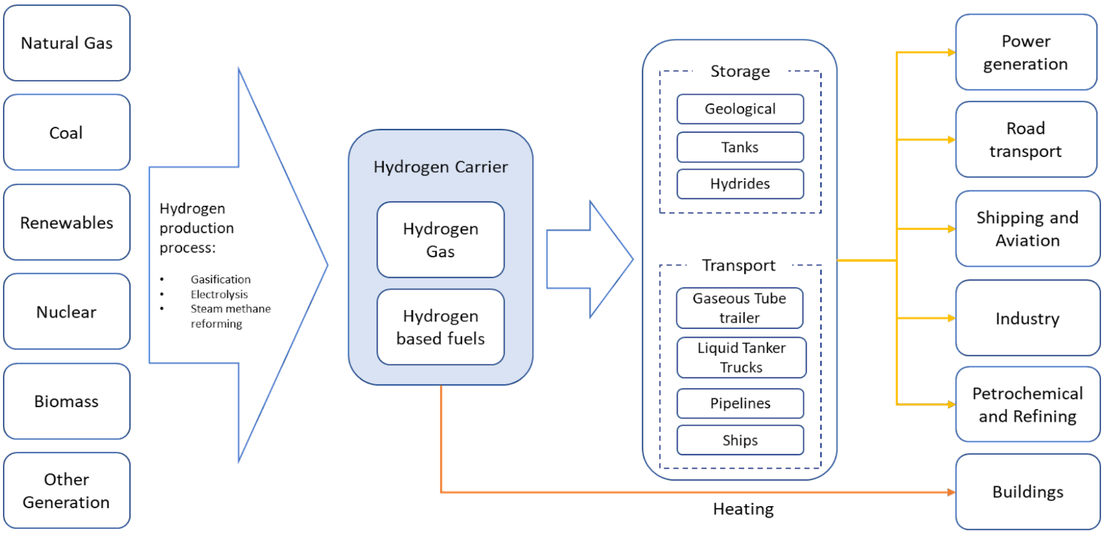

Figure 2 – Hydrogen supply chains: A simplified illustration[29]

2.3 Demand-side response

Demand-side response refers to a range of actions, such as reducing production during peak demand periods, shifting electricity-consuming activities to off-peak periods, which electricity consumers can do to reduce or shift their consumption, to help balance the

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[38] IEA (2022). Global Hydrogen Review. https://doi.org/10.1787/a15b8442-en.

[39] IRENA (2019). Hydrogen: A Renewable Energy Perspective–Report prepared for the 2nd Hydrogen Energy Ministerial Meeting in Tokyo. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective.

[40] Bocklisch, T. (2016). Hybrid energy storage approach for renewable energy applications. *Journal of Energy Storage*, 8, 311-319.

grid[41]. These actions can be incentivised by time-based pricing[42], also known as an implicit, price-based demand-side response[41], or a non-dispatchable demand-side response[43]. They can also be undertaken through agreements between system operators and electricity consumers, sometimes through an aggregator in the electricity markets[44]. This type of demand-side response is dispatchable, because system operators can request electricity consumers to change their consumption based on predetermined agreements for payments[43].

As estimated by the International Energy Agency, the global potential of demand-side response is currently about 4,000 TWh per year, equivalent to roughly 15% of total electricity demand. This potential could rise to 7,000 TWh by 2040, driven primarily by accelerated adoption of smart appliances and digital technologies (e.g., load management software, smart meters) that could enable better monitoring and control of the electricity-consuming equipment at the demand side[45].

2.4 Other technologies

Compressed air energy storage (CAES) is considered an attractive option for large-scale, long-duration energy storage, mainly due to its high round-trip efficiency (about 60%) and low cost when utilising abandoned mines[46]. Despite this attractiveness, commercialisation of CAES is likely to be affected by several factors, such as the high cost of artificial air storage using pressure vessels in areas with limited underground salt-cavern resources or mine tunnels for storage. Additional barriers include the inertia of compressor switching between energy storage and production, and the lack of economic incentives for its

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[41] IEA (2022). Demand response. https://www.iea.org/reports/demand-response.

[42] Eid, C., Koliou, E., Valles, M., Reneses, J., Hakvoort, R. (2016). Time-based pricing and electricity demand response: Existing barriers and next steps. *Utilities Policy*, 40, 15-25.

[43] Yang, C. J. (2017). Opportunities and barriers to demand response in China. *Resources, Conservation and Recycling*, 121, 51-55.

[44] Cardoso, C. A., Torriti, J., & Lorincz, M. (2020). Making demand side response happen: A review of barriers in commercial and public organisations. *Energy Research & Social Science*, 64, 101443.

[45] S. Bouckaert, T. Goodson, B. Wanner (2018). The clean energy transition requires action on electricity demand. https://www.iea.org/commentaries/the-clean-energy-transition-requires-action-on-electricity-demand.

[46] Borri, E., Tafone, A., Comodi, G., Romagnoli, A., Cabeza, L. F. (2022). Compressed Air Energy Storage—An Overview of Research Trends and Gaps through a Bibliometric Analysis. *Energies*, 15(20), 7692.

deployment[47].

Supercapacitor is a type of energy storage technology that uses electrostatic double-layer capacitance or pseudo capacitance for energy storage[48]. It has shown great potential as an important complement to battery storage due to its high power density (10 kW/kg), high charging and discharging rates, and long cycle life (more than 100,000 cycles)[49]. To realise this potential, however, several technical barriers need to be addressed including low energy density and the need for consistency detection[50].

Thermal energy storage can refer to a wide range of technologies that store energy in a material for later use in power generation and heating and cooling applications[51]. These technologies can be classified into four broad categories: sensible, latent, thermochemical and mechanical-thermal[51,52,53]. Sensible storage uses a material such as water and molten salt mixtures to store heat directly[53]. Latent storage is more complex and occurs when the phase of storage material is changed, for example, from solid to liquid, or from liquid to vapor, without a change in temperature. The stored energy will be released when the material returns to its original state[54]. In thermochemical storage, reversible chemical reactions are used to separate chemical compounds that can be recombined later to produce heat[55]. Thermal storage can also be coupled with mechanical storage systems

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[47] Tong, Z., Cheng, Z., Tong, S. (2021). A review on the development of compressed air energy storage in China: Technical and economic challenges to commercialization. *Renewable and Sustainable Energy Reviews*, 135, 110178.

[48] Bueno, P. R. (2019). Nanoscale origins of super-capacitance phenomena. *Journal of Power Sources*, 414, 420-434.

[49] Peng, H., Sun, X., Weng, W., & Fang, X. (2017). 6—Energy Storage Devices Based on Polymers. *Polymer Materials for Energy and Electronic Applications,* 197-242.

[50] Huang, S., Zhu, X., Sarkar, S., & Zhao, Y. (2019). Challenges and opportunities for supercapacitors. *APL Materials*, 7(10), 100901.

[51] Simó-Solsona, M., Palumbo, M., Bosch, M., Fernandez, A. I. (2021). Why it's so hard? Exploring social barriers for the deployment of thermal energy storage in Spanish buildings. *Energy Research & Social Science*, 76, 102057.

[52] Mahon, H., O'Connor, D., Friedrich, D., Hughes, B. (2022). A review of thermal energy storage technologies for seasonal loops. *Energy*, 239, 122207.

[53] RENA (2020). Innovation outlook: Thermal energy storage. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf.

[54] Cabeza, L. F., Martorell, I., Miró, L., Fernández, A. I., Barreneche, C. (2015). Introduction to thermal energy storage (TES) systems. In *Advances in Thermal Energy Storage Systems* (pp. 1-28). Woodhead Publishing.

[55] Pardo, P., Deydier, A., Anxionnaz-Minvielle, Z., Rougé, S., Cabassud, M., Cognet, P. (2014). A review on high temperature thermochemical heat energy storage. *Renewable and Sustainable Energy Reviews*, 32, 591-610.

(e.g., compressed air storage) to improve the overall efficiency of the energy storage system[53].

Virtual power plant (VPP) is a system management solution that connects different elements of a growing decentralised power system to balance supply with demand based on the application of advanced digital technologies, such as blockchains, cloud computing and Internet of Things (IoT). Figure 3 illustrates a virtual power plant and its key elements. Several trial VPP projects have already been undertaken in Australia, major European countries, and the United States, but its wider application is likely to be affected by several factors. One such factor is scheduling algorithms that are unable to deal with the complexity of an increasingly decentralised power system[56]. More recent models have sought to address this issue by using more advanced optimisation and heuristic methods to account for the complexity involved in the interactions between various market participants and different market mechanisms[57]. However, the proposed models have rarely been applied to real world cases to demonstrate their practicality.

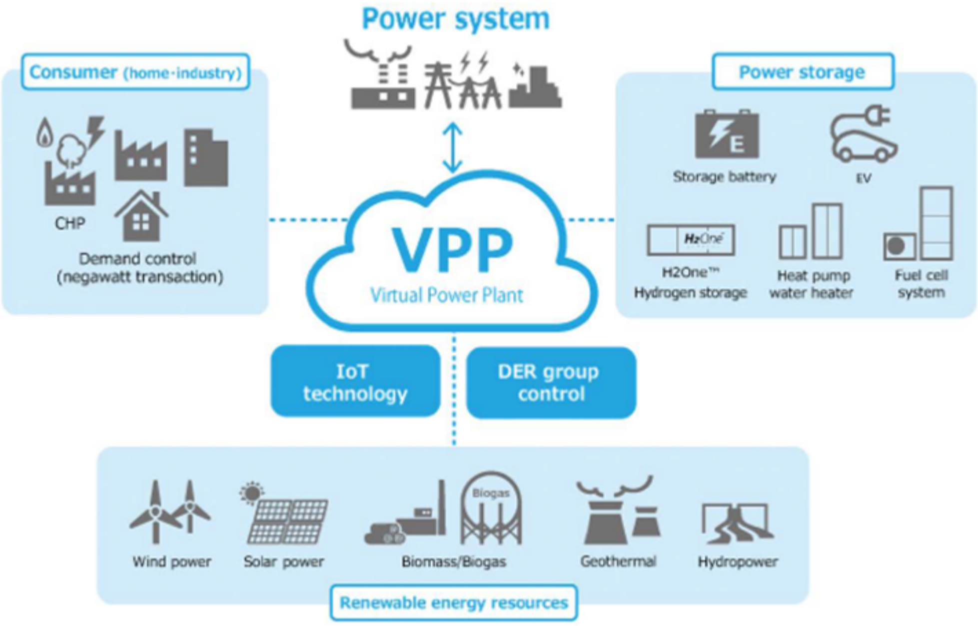

Figure 3 – An illustration of a virtual power plant and its key elements[58]

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[56] Zhang, J. (2022). The Concept, Project and Current Status of Virtual Power Plant: A Review. In *Journal of Physics: Conference Series* (Vol. 2152, No. 1, p. 012059). IOP Publishing.

[57] Naval, N., Yusta, J. M. (2021). Virtual power plant models and electricity markets-A review. *Renewable and Sustainable Energy Reviews,* 149, 111393.

[58] Swarupa, M. L., Lakshmi, G. S., Reddy, K. S. (2023). Practical Implementation of VPP in the Real World Based on Emerging Technologies. In *Virtual Power Plant Solution for Future Smart Energy Communities* (pp. 7-38). CRC Press.

Vehicle-to-grid (V2G) describes a system where plug-in electric vehicles (EVs) provide ancillary services by either supplying electricity back to the grids or throttling their charging rate[59]. However, the economic viability of vehicle-to-grid operations has been the subject of intense debate, and much of this debate has centred on the issue of battery degradation as an outcome of more frequent charging/discharging. Additional cycling to discharge EV batteries to the grids could affect battery life, adding additional costs to EV owners[60]. A more recent study suggests that this issue could be addressed by using a smart grid system integrated with EVs. In fact, such integration could even extend the life of the EV battery[61]. This is better considered as an indication of the future possibilities of V2G if the technology measures and guidelines outlined in their paper are embraced[59].

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[59] Uddin, K., Dubarry, M., Glick, M. B. (2018). The viability of vehicle-to-grid operations from a battery technology and policy perspective. *Energy Policy*, 113, 342-347.

[60] Dubarry, M., Devie, A., McKenzie, K. (2017). Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis. *Journal of Power Sources*, 358, 39-49.

[61] Uddin, K., Jackson, T., Widanage, W. D., Chouchelamane, G., Jennings, P. A., Marco, J. (2017). On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system. *Energy*, 133, 710-722.

3. Underlying factors of flexibility technologies uptake

This section discusses the underlying influencing factors for the uptake of various flexibility technologies considered in the previous section, based on a review of major publicly available studies on the topic (see Appendix A for details). This review helps to inform the design of the questionnaire. It is organised under three broad themes:

- technical feasibility and economic viability,
- enabling infrastructure, and
- regulatory and market arrangements.

3.1 Technical feasibility and economic viability

3.1.1 Coal power flexibilisation

Coal power flexibilisation is a technically proven technology that can be deployed at scale and that would allow less power to be generated from coal – importantly, the removal of coal combustion would create more space for clean energy in the grid. One key issue that may affect the uptake of coal power flexibilisation is that repeatedly slowing down the operation of heavy machinery can cause increased wear and tear on equipment and reduce the lifetime of the components. The frequent increase and decrease in demand (ramp-up and down) of a coal-fired power plant to provide load following services could cause rapid changes in process temperature, which increase the chance of thermal fatigue, thermal expansion, fireside corrosion and rotor bore cracking Temperature changes could, in turn, lead to increased rates of component life consumption[62]. Running the coal-fired power plant at a lower load would also reduce fuel efficiency and air pollutant control efficiency and hence lead to higher CO_2 and pollutant emissions per unit of output[63,64]. In addition, the introduction of carbon penalties, such as carbon pricing and intensity-based

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[62] Hesler, S. (2011) Mitigating the effects of flexible operation on coal-fired power plants, Power. https://www.powermag.com/mitigating-the-effects-of-flexible-operation-on-coal-fired-power-plants/.

[63] Clean Energy Ministerial (2018) Thermal power plant flexibility. https://www.cleanenergyministerial.org/resource/thermal-power-plant-flexibility-2018-a-publication-under-the-clean-energy-ministerial-campaign/

[64] Henderson, C. (2014). Increasing the flexibility of coal-fired power plants. IEA Clean Coal Centre, https://usea.org/sites/default/files/092014_Increasing%20the%20flexibility%20of%20coal-fired%20power%20plants_ccc242.pdf.

emissions trading, could put upwards pressure on the cost of coal generation, which may discourage the use of coal to provide flexibility services.

Coal power flexibilisation is also considered cheaper when compared with other flexibility technologies. It is estimated that the fixed cost of retrofitting an existing coal-fired power plant is in the range of 600 to 700 Yuan/kW, compared to 6,300-7,200 Yuan/kW for pumped hydro[65]. It is also worth noting that the economic viability of coal power flexibilisation could be affected by the introduction of carbon pricing that increases the cost of coal generation[66].

3.1.2 Pumped hydro

Pumped hydro is technically mature and ready for large-scale deployment, but its deployment is often affected by geological constraints. A favourable landscape topography requires a certain head difference and slope between the two reservoirs of pumped hydro storage. Head difference refers to the height difference between the space in which water enters into the hydro system and where it leaves. Artificially developing the required head and slope often results in increased construction time and cost[67]. Long lead times, high development costs (e.g., capital costs, costs involved in land acquisition and infrastructure construction), and long payback periods are therefore often cited as major barriers to pumped hydro projects[28,68].

3.1.3 Battery storage

Battery storage technologies, especially lithium-based batteries, have emerged as a popular option for grid-scale energy storage, primarily due to substantial cost reductions. Nonetheless, the upfront costs for deploying battery storage systems remain high when

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[65] NRDC (2022). 电力系统灵活性提升：技术路径、经济性与政策建议. http://www.nrdc.cn/Public/uploads/2022-07-18/62d4c2e313df1.pdf.

[66] Garðarsdóttir, S. Ó., Göransson, L., Normann, F., Johnsson, F. (2018). Improving the flexibility of coal-fired power generators: Impact on the composition of a cost-optimal electricity system. *Applied Energy*, 209, 277-289.

[67] Görtz, J., Aouad, M., Wieprecht, S., Terheiden, K. (2022). Assessment of pumped hydropower energy storage potential along rivers and shorelines. *Renewable and Sustainable Energy Reviews*, 112027.

[68] Connolly, D., Lund, H., Mathiesen, B. V., Pican, E., Leahy, M. (2012). The technical and economic implications of integrating fluctuating renewable energy using energy storage. *Renewable Energy*, 43, 47-60.

compared with more mature technologies, such as coal power and pumped hydro[23,69,70,71]. The recent surge in raw material and battery component prices has further accentuated this challenge, as lithium-ion battery prices rose in 2022 after more than a decade of decline, starting in 2010 (see Figure 4). The battery price increase suggests that further cost reductions rely not only on technological innovation, but also on mineral prices. The upfront costs for second-life battery storage systems are lower (about 20% to 35%) than new systems, but their adoption could be affected by various techno-economic issues, such as shorter operating life, lower depth of discharge and high electricity prices[69,72].

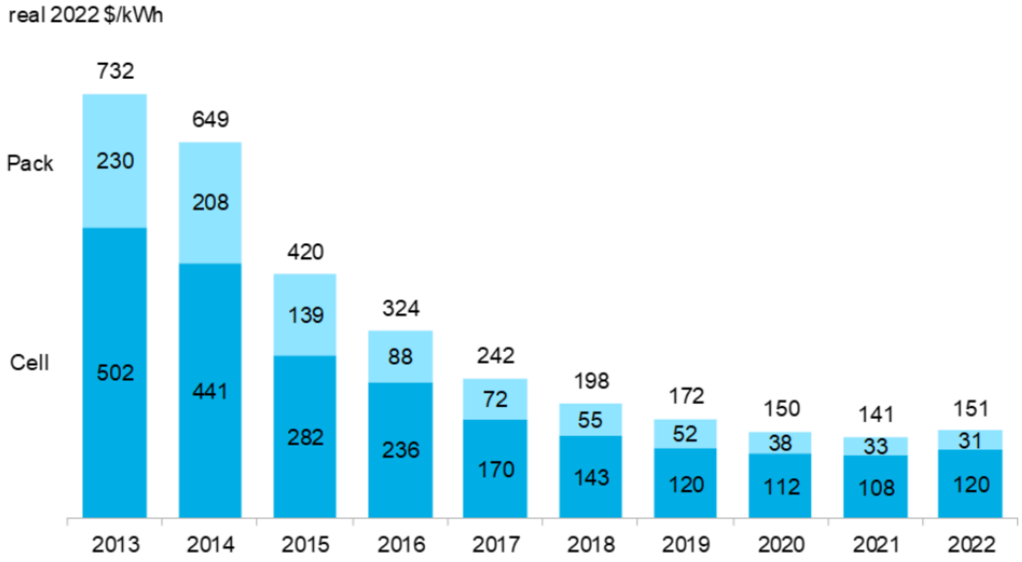

Figure 4 – 2013–2022 Volume-weighted average lithium-ion battery prices[73]

3.1.4 Hydrogen

Clean hydrogen, which includes renewable-based hydrogen produced through electrolysis and fossil-based hydrogen equipped with CCS, is expected to play an important part in the

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[69] Song, Z., Feng, S., Zhang, L., Hu, Z., Hu, X., Yao, R. (2019). Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: Real case scenarios. *Applied Energy*, 251, 113411.

[70] Bhatnagar, D., Currier, A. B., Hernandez, J., Ma, O., Kirby, B. (2013). Market and policy barriers to energy storage deployment (No. SAND2013-7606). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); United States, Washington, DC.

[71] Schmidt, O., Hawkes, A., Gambhir, A., Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. *Nature Energy*, 2(8), 1-8.

[72] Steckel, T., Kendall, A., Ambrose, H. (2021). Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems. *Applied Energy*, 300, 117309.

[73] BloombergNEF (2022). Lithium-ion battery pack prices rise for first time to an average of $151/kWh. https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/.

electricity transition, providing a viable solution for long-duration energy storage. Several major technical and economic issues, however, need to be addressed to enable the wider adoption of hydrogen as a fuel. For example, almost all hydrogen produced today is used in oil refining and ammonia production. Extending the use of hydrogen to the electricity sector will requires significant technological advancements to redress safety challenges such as, ease of leaking as a gaseous fuel, low energy ignition, and wide range of flammable concentrations in the air[74,75,76].

Producing hydrogen from low-carbon sources, either renewable electricity, nuclear or combustible fuels equipped with carbon capture, utilisation and storage facilities (CCUS), is also costly, despite recent reductions in the cost of hydrogen electrolysis. According to the IEA, the average cost of hydrogen production from natural gas is USD 1.0-2.5/kg without CCUS and USD 1.5-3.0/kg with CCUS. The average cost of renewable-based hydrogen is USD 4.0-9.0/kg[38] . The main factors responsible for the high costs of hydrogen production include the use of precious metals (e.g., iridium and platinum) in production and storage facilities, as well as high installation costs. It is also worth noting that the recent surge in natural gas and oil prices is likely to improve the competitiveness of renewables-based hydrogen. According to the IEA, the costs of offshore wind-based hydrogen in Europe and solar-based hydrogen in the Middle East and China would become cheaper than natural gas-based hydrogen when gas prices increase to more than USD 25/MMBtu (Million Btu)[38].

3.1.5 Thermal energy storage – molten salt storage

Molten salt storage, a form of sensible thermal energy storage technology, is currently the most widely used thermal storage technology in the power sector with a total capacity of more than 21 GWh installed worldwide, due to its relatively high technological readiness compared to other thermal storage technologies[53]. Thermal energy storage is often used with concentrated solar power (CSP) plants to store energy during the day and discharge it

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[74] San Marchi, C., Hecht, E. S., Ekoto, I.W., and others (2017). Overview of the DOE hydrogen safety, codes and standards program, part 3: Advances in research and development to enhance the scientific basis for hydrogen regulations, codes and standards. *International Journal of Hydrogen Energy*, 42(11), 7263-7274.

[75] Tolias, I. C., Giannissi, S. G., Venetsanos, A. G., and others (2019). Best practice guidelines in numerical simulations and CFD benchmarking for hydrogen safety applications. *International Journal of Hydrogen Energy*, 44(17), 9050-9062.

[76] Moradi, R., Groth, K. M. (2019). Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy*, 44(23), 12254-12269.

at night[77]. Other thermal storage technologies are at the applied research, prototype or demonstration stage of development and have not yet reached commercialisation (see Figure 5). To upscale deployment of thermal storage technologies, substantial research is needed to improve performance in terms of round-trip efficiency, lifespan and operating temperature[53].

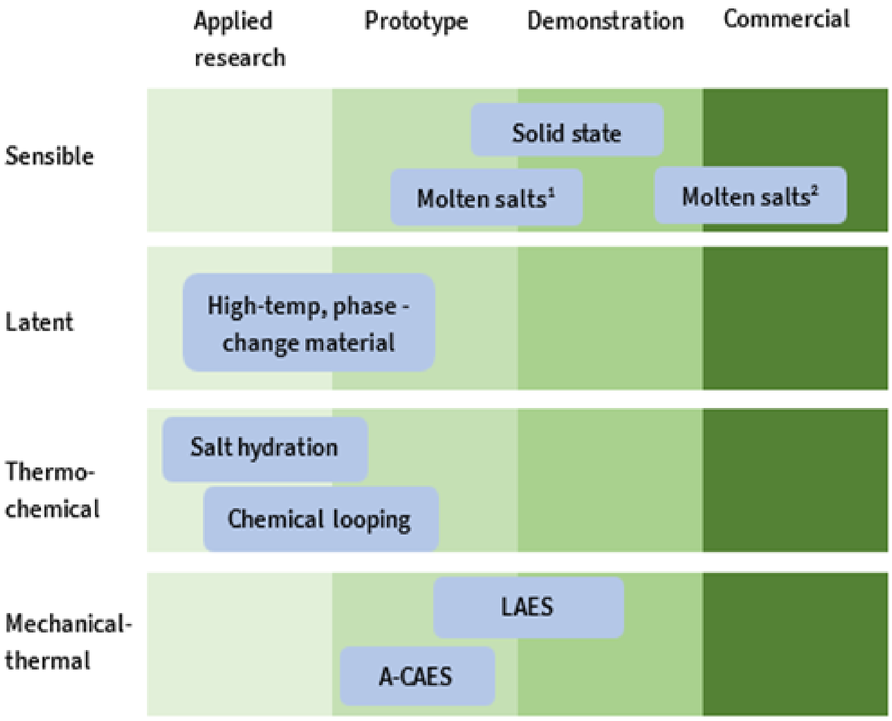

Figure 5 – Technological readiness of thermal storage technologies[53]

Notes: 1. Standalone system; 2. Coupled with CSP system; 3. A-CASES: adiabatic compressed air energy storage; 4. LAES: liquid air energy storage.

3.2 Enabling infrastructure

Fossil-based and low-carbon flexibility technologies have different requirements for infrastructure. The lack of necessary infrastructure could be a major constraint on the deployment of low-carbon flexibility. For example, coal power flexibilisation often involves retrofitting existing power plants with well-prepared infrastructure. Similarly, ideal sites for pumped hydro can sometimes be found in areas far away from the existing road and transmission infrastructure, making their development expensive[28].

One particular issue holding back the widespread adoption of hydrogen is the lack of

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[77] Bauer, T., Odenthal, C., Bonk, A. (2021). Molten salt storage for power generation. *Chemie Ingenieur Technik*, 93(4), 534-546.

infrastructure to transport, distribute, store and dispense hydrogen as a fuel for stationary uses[78,79,80]. Repurposing natural gas pipelines for hydrogen transportation can reduce investment costs by 50-80%, but there appears to be limited practical experience to guide its implementation[38].

More active demand-side response also requires a range of enabling infrastructure, such as smart meters, sensors, communication technology and the IoT. These technologies will be needed to automatically monitor and control electricity-consuming activities at the demand side[81,82]. Development of the necessary technology could be affected by factors such as the lack of standardisation and protocols for metering and Information and Communication Technology (ICT)[82,83], or technical unreadiness (for example, ICT-based demand-side management tools) integral to more active demand-side response[84]. Concerns about data security and privacy[85], as well as significant investments required to deploy more sophisticated technologies could also be barriers[42,86,87].

3.3 Regulatory and market arrangements

Reconfiguring the power system to improve its flexibility will require introducing and optimising regulatory and market arrangements that enable the uptake of various flexibility technologies. One particular area for improvement is the ancillary service

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[78] Dell, R. M., Moseley, P. T., Rand, D. A. J. (2014). Hydrogen, fuel cells and fuel cell vehicles. Towards sustainable road transport, *Academic Press*, Boston, 260-295.

[79] Staffell, I., Scamman, D., Abad, A. V., and others (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, 12(2), 463-491.

[80] Hydrogen Council (2017). Hydrogen Scaling Up. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf.

[81] Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy*, 36(12), 4419-4426.

[82] Good, N., Ellis, K. A., Mancarella, P. (2017). Review and classification of barriers and enablers of demand response in the smart grid. *Renewable and Sustainable Energy Reviews*, 72, 57-72.

[83] D'Ettorre, F., Banaei, M., Ebrahimy, R., others (2022). Exploiting demand-side flexibility: State-of-the-art, open issues and social perspective. *Renewable and Sustainable Energy Reviews*, 165, 112605.

[84] Crosbie, T., Broderick, J., Short, M., Charlesworth, R., Dawood, M. (2018). Demand response technology readiness levels for energy management in blocks of buildings. *Buildings*, 8(2), 13.

[85] Paterakis, N. G., Erdinç, O., Catalão, J. P. (2017). An overview of Demand Response: Key-elements and international experience. *Renewable and Sustainable Energy Reviews*, 69, 871-891.

[86] Cappers, P., MacDonald, J., Goldman, C., Ma, O. (2013). An assessment of market and policy barriers for demand response providing ancillary services in US electricity markets. *Energy Policy*, 62, 1031-1039.

[87] Kim, J. H., Shcherbakova, A. (2011). Common failures of demand response. *Energy*, 36(2), 873-880.

market, where various flexibility-service suppliers can help smooth out frequency imbalances or variable wind and solar generation. The absence or underdevelopment of ancillary service markets could lead to insufficient remuneration to service providers, discouraging them from investing in new projects[88]. Another area for improvement is capacity remuneration mechanisms, through which ‘extra’ generation capacity is secured to ensure supply adequacy in rare situations, such as extremely high demand on a hot summer day[89].

While well-established ancillary services and capacity markets are crucial for the uptake of all flexibility technologies, some regulatory and market-related issues are specific to particular technologies. Key issues include:

- the treatment of battery storage as generation assets that precludes its application for transmission and distribution investment deferral (using storage to manage bottlenecks in the grids), because network companies are not allowed to own storage assets[26],
- unclear classification of battery storage and demand-side response as eligible ancillary service providers in the market[90],
- no time-of-use tariffs that enable access to low-cost electricity for charging pumped hydro and battery storage[91,92,93], and
- charging grid fees for electricity consumed for refilling hydro reservoirs or charging batteries[94].

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[88] Gissey, G. C., Dodds, P. E., Radcliffe, J. (2018). Market and regulatory barriers to electrical energy storage innovation. *Renewable and Sustainable Energy Reviews*, 82, 781-790.

[89] Aagaard, T. S., Kleit, A. N. (2022). Reliability and the Missing Money Problem, in *Electricity Capacity Markets*. Cambridge University Press, pp. 37–53.

[90] Deloitte (2018). Supercharged: Challenges and opportunities in global battery storage markets. https://view.deloitte.nl/rs/502-WIB-308/images/gx-er-challenges-opportunities-global-battery-storage-markets.pdf.

[91] Zhang, S., Andrews-Speed, P., Perera, P. (2015). The evolving policy regime for pumped storage hydroelectricity in China: A key support for low-carbon energy. *Applied Energy*, 150, 15-24.

[92] Ming, Z., Kun, Z., Daoxin, L. (2013). Overall review of pumped-hydro energy storage in China: Status quo, operation mechanism and policy barriers. *Renewable and Sustainable Energy Reviews*, 17, 35-43.

[93] Sivakumar, N., Das, D., Padhy, N. P., and others (2013). Status of pumped hydro-storage schemes and its future in India. *Renewable and Sustainable Energy Reviews*, 19, 208-213.

[94] Papapetrou, M. Maidonis, T., Garde, R., Garcia, G. (2013). European regulatory and market framework for electricity storage infrastructure. https://www.store-project.eu/documents/results/en_GB/european-regulatory-and-market-framework-for-electricity-storage-infrastructure.

4. Experts' perceptions towards flexibility technologies in China

This section presents the results of an expert survey designed to understand the perceptions held by energy experts in China towards various flexibility technologies (see Appendix B for questionnaire). The survey involved 38 domain experts from public agencies, industry associations, utility companies, research institutes, universities, governmental departments and non-governmental organisations (NGO) that have actively engaged in the electricity sector in China. In the questionnaire, specific emphasis is given to factors that are likely to affect the uptake of flexibility technologies. The selection of factors is informed by the discussion presented in the previous section. Some experts were also interviewed for further clarification.

4.1 Technical feasibility

Technical feasibility considers several factors including technical readiness, engineering complexity, access to patents, and cleanliness.

4.1.1 Technical readiness

Technical readiness, in the context of this report, is referred to as the degree of maturity of a technology for large-scale adoption. Table 2 presents the expert survey results that describe the perceived readiness of various flexibility technologies: concept phase, proof of concept phase, market introduction phase, and wider adoption phase.

The results suggest that only coal power flexibilisation, pumped hydro, lithium-ion battery, and vehicle-to-grid are perceived to be mature and ready for wider adoption. Other technologies are seen as either at the research (conceptualisation) and development (proof of concept through demonstration projects) stages, or at an early stage of market introduction.

Table 2 – Technical readiness

		Concept	Proof of concept	Market introduction	Wider adoption	Don’t know
Coal power flexibilisation		13%	0%	13%	74%	0%
Pumped hydro		10%	0%	3%	87%	0%
Battery storage	Lithium-ion	4%	0%	14%	75%	4%
	Sodium-ion	5%	47%	21%	11%	16%
	Lead-acid	0%	0%	16%	68%	16%
	Flow	15%	25%	25%	15%	20%
Hydrogen	Electrolysis	11%	50%	25%	7%	7%
	Fossil	12%	29%	12%	29%	18%
Demand-side response		7%	21%	31%	27%	14%
Compressed air storage		9%	45%	18%	9%	18%
Thermal storage		14%	29%	10%	24%	23%
Supercapacitor		17%	28%	17%	17%	22%
Superconducting Magnetic		38%	25%	6%	6%	25%
Flywheel		15%	40%	10%	15%	20%
Virtual power plant		8%	32%	28%	24%	8%
Vehicle-to-grid		8%	8%	4%	68%	12%
Gravity storage		16%	42%	0%	11%	32%

Note: About 3% of the surveyed experts indicated that while lithium-ion battery is mature and at the stage of market introduction, some of its supplementary technologies, such as battery management techniques, remain at an early stage of development (i.e., concept stage).

One issue related to technical readiness is safety. This issue is particularly acute for hydrogen, because 42% to 54% of the survey respondents indicated that additional care is required to ensure the safety of the hydrogen supply (see Table 3). This is understandable, considering hydrogen has a wide range of flammable concentrations in the air and lower ignition energy than gasoline or fossil gas, meaning that it can ignite more easily. More than one-quarter of survey respondents expressed concern about the safety of lithium-ion and sodium-ion battery storage (see Table 3), possibly because components in the battery packages may break down at elevated temperatures, causing fire hazards. Indeed, in the *Twenty-Five Key Requirements for Preventing Power Production Accidents* released by the National Energy Administration of China in 2022, medium and large energy storage stations are advised not to use ternary lithium and sodium-sulphur batteries[95].

Table 3 – Safety

		Not a major concern	Additional care required	Don't know
Coal power flexibilisation		77%	10%	13%
Pump hydro		90%	3%	7%
Battery storage	Lithium-ion	50%	32%	18%
	Sodium-ion	37%	26%	37%
	Lead-acid	53%	11%	37%
	Flow	40%	20%	40%
Hydrogen	Electrolysis	29%	54%	17%
	Fossil	29%	42%	29%
Demand-side response		76%	7%	17%
Compressed air storage		32%	32%	36%
Thermal storage		33%	24%	43%
Supercapacitor		44%	11%	44%
Superconducting Magnetic		38%	25%	6%
Flywheel		40%	15%	45%
Virtual power plant		72%	12%	16%
Vehicle-to-grid		64%	20%	16%
Gravity storage		42%	11%	47%

4.1.2 Engineering complexity

Engineering complexity is about the complexity involved in project development and manufacturing required equipment and parts. Flexibility technologies with high degrees of

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[95] NEA (2022) Twenty-Five Key Requirements for Preventing Power Production Accidents. http://www.nea.gov.cn/2022-06/29/c_1310635544.htm.

readiness, such as coal power flexibilisation, pumped hydro, and lithium-ion batteries, are considered to have less engineering complexity, with more than 75% of survey respondents indicating that engineering complexity is ‘less of a concern’ for these technologies (see Figure 6).

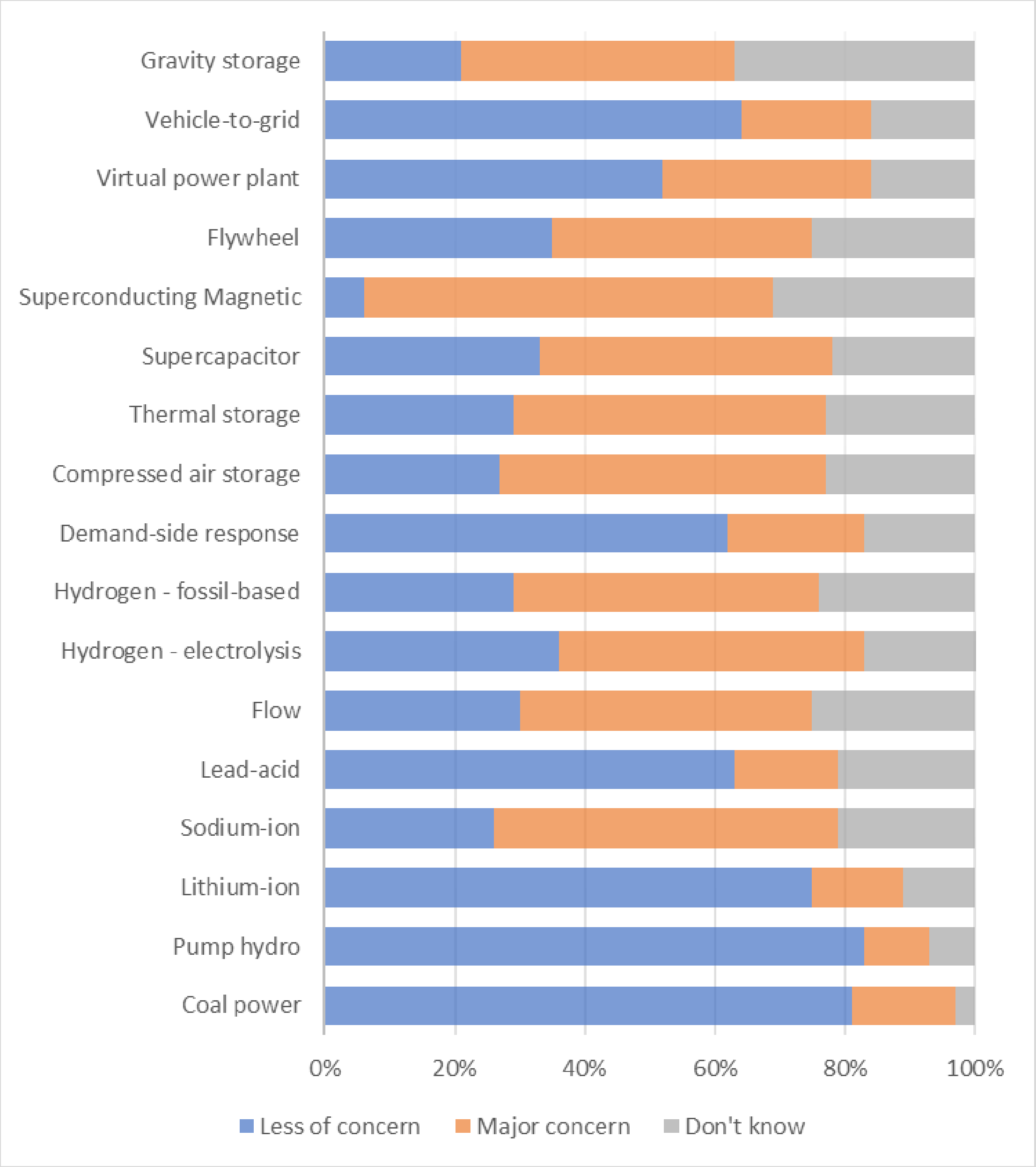

Figure 6 – Engineering complexity of flexibility technologies

More than 50% of experts participating in the survey considered engineering complexity as ‘less of a concern’ for demand-side response, virtual power plant and vehicle-to-grid technologies. This can be explained by the fact that these technologies are ‘soft’, meaning their deployment is largely dependent on the availability of enabling platforms based on general purpose technologies, such as information technologies, and behavioural change.

Engineering complexity is considered ‘a major concern’ for some emerging technologies, for example, sodium-ion and flow batteries, compressed air energy storage, supercapacitor and thermal energy storage, which could be because these technologies are at an early stage of development and have not yet demonstrated their technical feasibility. Engineering complexity is perceived by the surveyed experts as a major concern for both green and fossil-based hydrogen. This is primarily because hydrogen is relatively difficult to store when compared with fossil gas because it has a low density and requires more space and larger storage.

4.1.3 Access to core patents

Access to core patents required for developing various flexibility technologies could affect the perceptions held by experts regarding the feasibility of these technologies. This issue seems to be less of a concern in China, as the survey results show a widespread agreement among the experts that China has at least partial access to core patents required for developing flexibility technologies (see Figure 7). Interestingly, when asked if access to core patents would impact technological development and deployment, 40% to 79% of the respondents responded ‘don’t know’ for some emerging technologies, such as flow battery, sodium-ion battery, supercapacitor, superconducting magnetic energy storage, and gravity storage. This is likely due to the relative newness of the technologies.

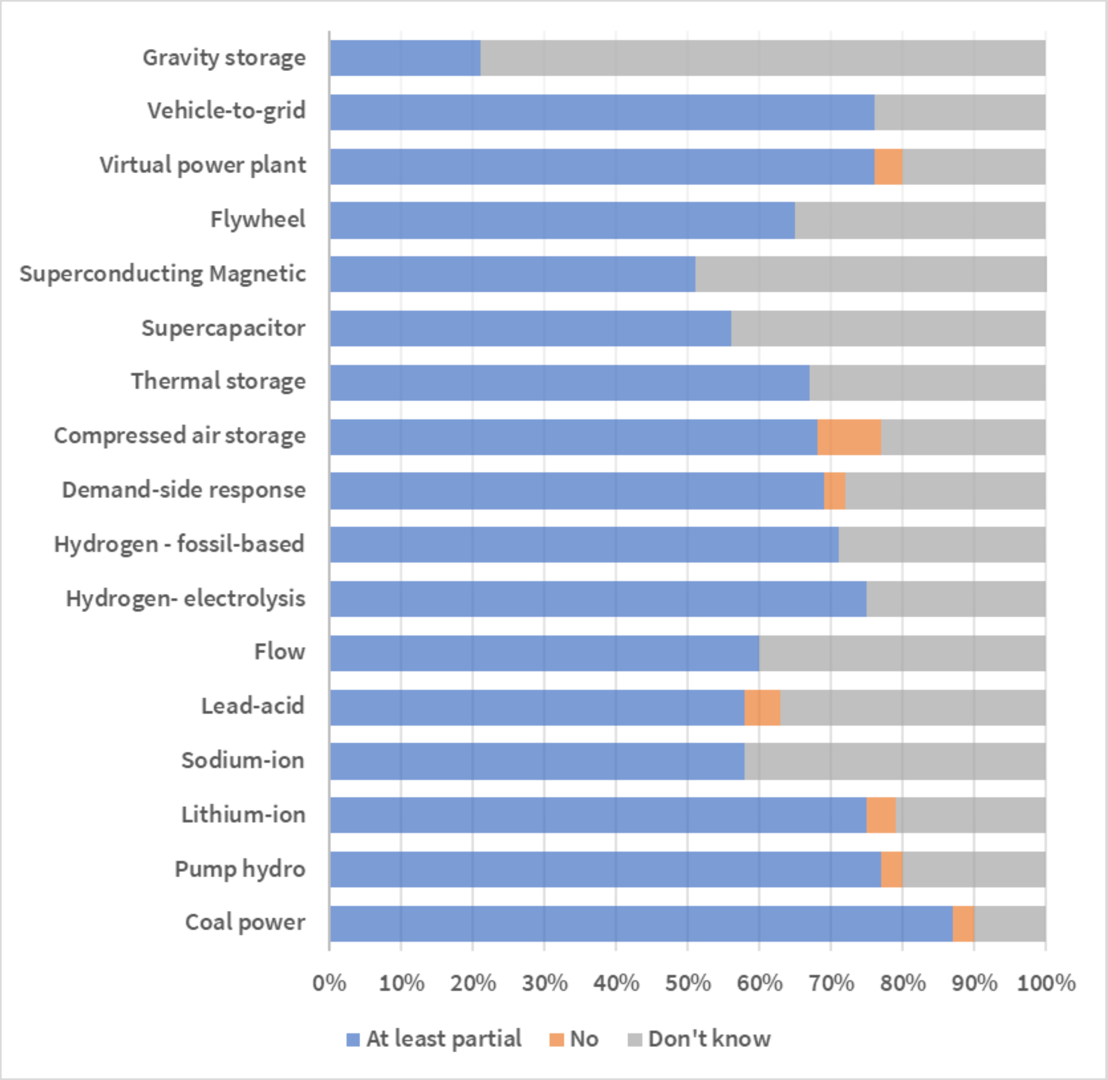

Figure 7 – Percentage of respondents answering the question: Would access to core patents impact the development of flexibility technologies?

4.1.4 Cleanliness

The cleanliness of various flexibility technologies is assessed, in the context of this report, in terms of energy efficiency, greenhouse gas (GHG) emissions and pollutant emissions. The assessment results, as presented in Table 4, suggest a widely held view among the surveyed experts that the deployment of flexibility technologies, in general, will improve energy efficiency in the electricity sector and help lower its GHG and pollutant emissions. This is understandable, since flexibility has been widely recognised as a key enabler for integrating a high share of variable renewable energy sources and is therefore an important contributor to higher energy efficiency and lower electricity supply emissions.

Table 4 – Cleanliness (% of positive response)

		Energy efficiency	GHG emissions	Pollutant emissions
Coal power flexibilisation		32%	53%	37%
Pump hydro		37%	70%	60%
Battery storage	Lithium-ion	32%	43%	29%
	Sodium-ion	17%	39%	22%
	Lead-acid	31%	37%	21%
	Flow	21%	42%	26%
Hydrogen	Electrolysis	18%	68%	57%
	Fossil	23%	47%	41%
Demand-side response		62%	67%	56%
Compressed air storage		36%	59%	45%
Thermal storage		38%	48%	43%
Supercapacitor		33%	57%	39%
Superconducting Magnetic		33%	47%	40%
Flywheel		40%	60%	45%
Virtual power plant		50%	60%	56%
Vehicle-to-grid		40%	56%	72%
Gravity storage		32%	53%	37%

In the expert survey, demand-side response (including vehicle-to-grid), pumped hydro, and hydrogen electrolysis were seen as the preferable technologies from the perspective of GHG and air pollutant emissions. Some surveyed experts explained that using coal power plants as a source of flexibility means that those plants run at low loads, which could reduce fuel efficiency and lead to higher CO_2 and pollutant emissions per unit of output. One expert said large-scale coal-fired power units were used to provide peak regulation services in the Zhejiang province, which increased the wear and tear on equipment and reduced fuel efficiency. Reduced efficiency, together with high coal prices, has put pressure on the profitability of coal-fired power plants.

Some surveyed experts said pumped hydro, battery storage and green hydrogen could have adverse impacts on the efficiency of electricity supply due to energy losses in the conversion process, wherein electricity is stored in the forms of electrochemical (hydrogen and battery) or mechanical (pumped hydro) energy and converted back when needed. It is however worth noting that this is a common issue for all energy storage technologies, and battery storage and pumped hydro are often considered as having higher conversion efficiency. Additionally, some experts mentioned that energy storage technologies might contribute to higher GHG and pollutant emissions if the stored electricity is produced from fossil fuels, but that issue would become less important if energy storage is paired with renewable capacity.

Demand-side technologies, such as demand-side response, virtual power plant and vehicle-to-grid, received positive responses in the expert survey in terms of their impact on efficiency improvement (40% to 62%) and emissions reduction (45% to 72%). The favourable responses can be explained by the fact that rational electricity-consuming behaviours enabled by these technologies could shift the demand from shortage periods to other times. This could reduce the need for excessive supply-side flexibility capacity, which may lower the efficiency of the electricity supply and contribute to higher emissions, as discussed above.

4.1.5 Technical capacity to provide flexibility services

To ensure the reliability and security of electricity supply, a power system needs to have a range of flexibility services, from short- (millisecond) to medium-term (daily or weekly) responses to sudden changes in electricity supply and demand, as well as the management of long-term, seasonal variations in renewable generation. While a wide range of technologies are perceived to have the capacity to provide short- and medium-term flexibility services, only coal power and hydrogen, as shown in Table 5, are considered as having the capacity to manage long-term, seasonal variations in electricity supply.

Some experts participating in the survey were concerned that operating a coal-fired power plant more flexibly would cause increased wear and tear on equipment. One expert pointed out that ‘in theory, hydrogen has the capacity to manage seasonal variations in electricity supply, but the current hydrogen production capacity in China is inadequate to support this’. Some experts also mentioned that compressed air energy storage and thermal storage have demonstrated potential to help manage seasonal variations in renewable energy via several demonstrative projects, such as a large molten salt energy storage project combined with concentrated solar power in Qinghai.

Table 5 – Technical capacity (% of positive response)

		Short-term	Medium-term	Long-term	Don't know
Coal power flexibilisation		23%	22%	48%	16%
Pump hydro		10%	53%	27%	10%
Battery storage	Lithium-ion	50%	29%	7%	14%
	Sodium-ion	40%	35%	5%	20%
	Lead-acid	50%	25%	5%	20%
	Flow	53%	29%	9%	19%
Hydrogen	Electrolysis	4%	22%	54%	21%
	Fossil-based	6%	23%	41%	29%
Demand-side response		32%	47%	7%	14%
Compressed air storage		18%	41%	23%	18%
Thermal storage		19%	38%	24%	19%
Supercapacitor		56%	16%	6%	22%
Superconducting Magnetic		50%	12%	6%	31%
Flywheel		50%	25%	5%	20%
Virtual power plant		38%	42%	8%	12%
Vehicle-to-grid		38%	42%	4%	16%
Gravity storage		37%	10%	25%	26%

Note: *short-term* means flexibility services required to manage near instant (millisecond) to sub-hourly variations in supply and demand. *Medium-term* means flexibility services needed to manage daily or weekly variations in supply and demand. *Long-term* means flexibility services required to manage seasonal variations in electricity supply that often last for several weeks.

4.2 Economic viability

Flexibility technologies, excluding coal power flexibilisation and demand-side response, are considered by the surveyed experts as less economically viable with a payback period of more than five years, in the current power system and regulatory system (see Figure 8).

Several experts suggested that pumped hydro projects often have long lead times and high development costs, which cause a long payback period. In contrast, one expert pointed out that retrofitting a coal power plant often takes less than three months, whereas it usually takes five to six years to build a pumped hydro station. The same expert addressed the results presented in a recent IEA report: in Southeast Asia, battery storage will first become cost competitive in Vietnam in 2030 and then gradually come to other countries in the following years[96]. The expert concluded that battery storage and hydrogen are not yet mature enough to be deployed on a large scale. While retrofits of existing coal power plants can be implemented quickly, the development of new coal power capacity also takes several years.

Another expert mentioned that the current approach adopted in some Chinese provinces to procure demand-side response is not cost competitive: 'In Zheijiang, there are roughly 60,000 enterprises enrolled in the demand-side response program…they get paid to reduce their electricity usage…$4 yuan per kWh…to fill rising supply shortfalls in the hot summer days this year, lots of demand-side response services were procured…from July to early August alone, the total payment made to demand-side response providers went up to $700 million yuan…this put substantial financial pressure on local electricity suppliers'.

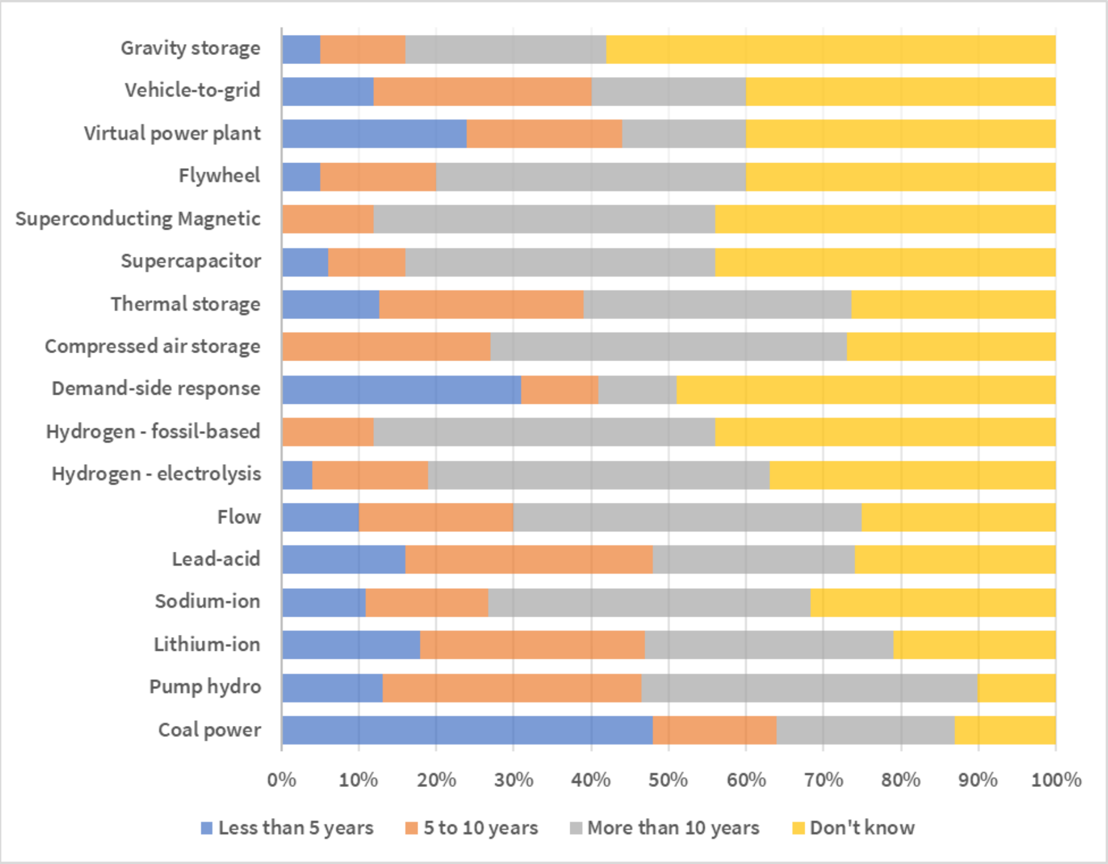

Figure 8 – Payback period for different flexibility technologies

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[96] IEA (2022). Southeast Asia Energy Outlook 2022. https://iea.blob.core.windows.net/assets/e5d9b7ff-559b-4dc3-8faa-42381f80ce2e/SoutheastAsiaEnergyOutlook2022.pdf.

4.3 Market arrangements

The survey asked participants about the importance of the market as a factor in the uptake of various flexibility technologies, and Figure 9 presents the survey results, which suggest experts widely agree that the market is crucial for uptake. Several experts who participated in the survey emphasised the need to strengthen the ancillary service market further and consider the introduction of some forms of capacity remuneration mechanisms in China to support the deployment of flexibility technologies.

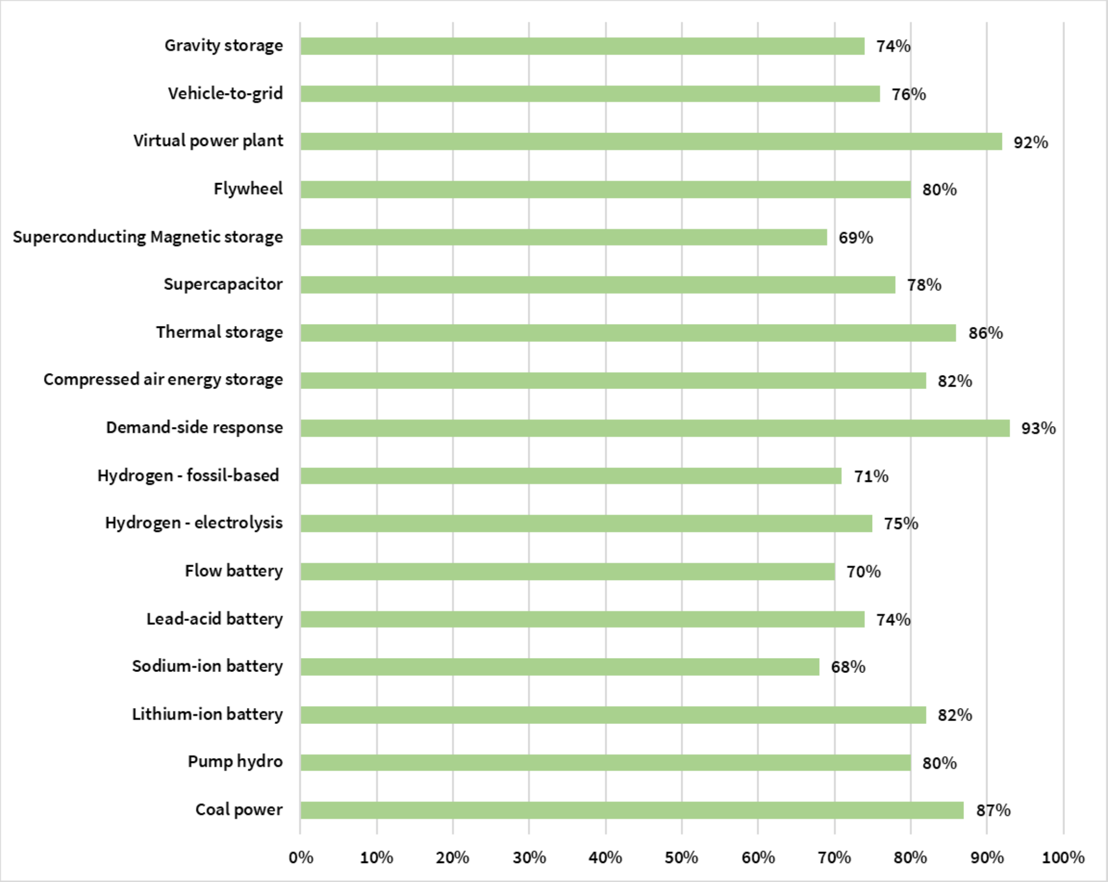

Figure 9 – Importance of market arrangements (% of participants who answered ‘yes’)

4.4 Policy support

Almost all experts participating in the survey indicated that the existing policy support to deploy flexibility technologies in China needs to be strengthened (see Figure 10).

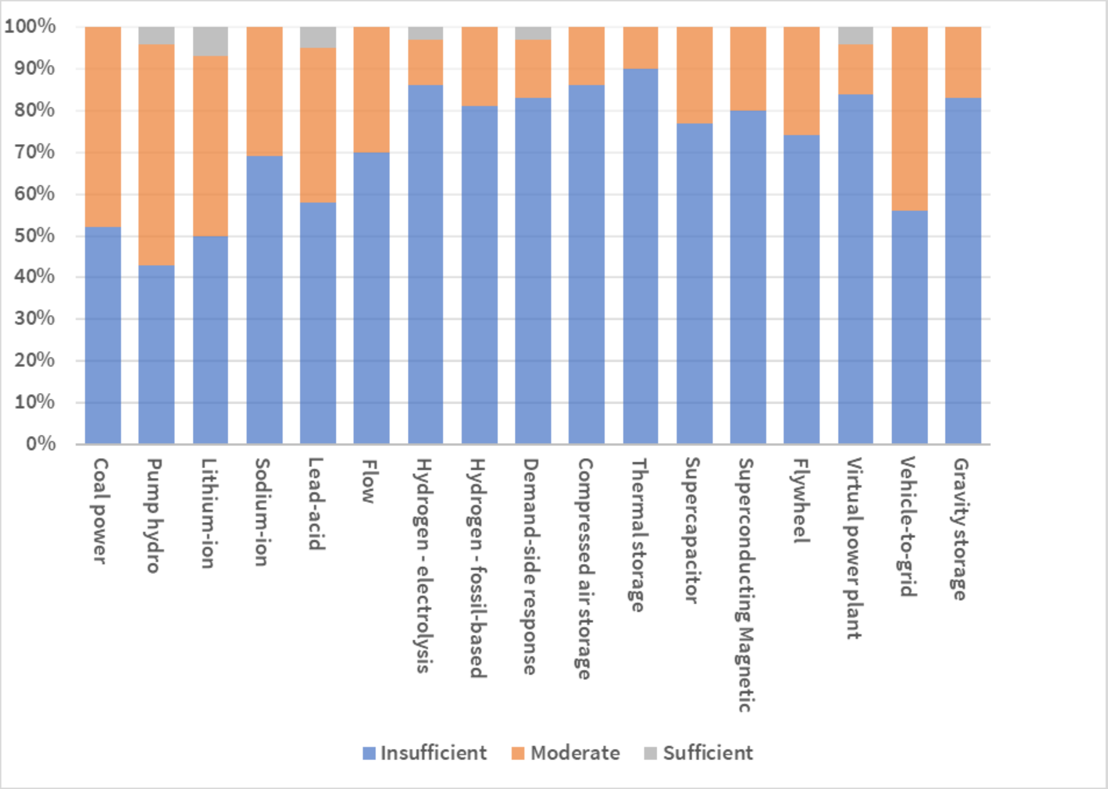

Figure 10 – Importance of policy support on flexibility technologies deployment

The experts were asked to list three priority areas where they believe additional policy intervention would be needed. The results are presented in Table 6. The responses from the experts participating in the survey suggest that technical feasibility is not perceived as a priority area for policy intervention for coal power, pumped hydro, lithium-ion battery, and demand-side technologies. The expert views are understandable considering that the technologies are mature and ready for wider adoption. Technologies at an early stage of development will require some form of policy support (see Section 3.1).

Economic viability is a priority area for policy intervention for all flexibility technologies, which could be due to the underdevelopment of electricity markets in China for procuring ancillary and capacity services. This is also confirmed by the survey results discussed in Section 4.3.

Infrastructure development is considered a priority area for policy intervention for battery storage, hydrogen, thermal storage, virtual power plant and vehicle-to-grid. In the case of battery storage, this is probably because the uptake of battery storage will present a serious waste-treatment challenge. Mounting numbers of waste batteries, if not treated properly, would release heavy metals and toxic chemicals into the natural environment, causing soil contamination and water pollution. Infrastructure would therefore need to be developed to collect, store, and recycle waste batteries. Lack of pipeline and shipping infrastructure is also often considered one of the main barriers for hydrogen development (see Section 3.2).

Table 6 – Priority areas for policy intervention

		Technical readiness	**Economic viability**	**Infrastructure**	**Demand**	**Motivation**
Coal power		3%	60%	10%	7%	30%
Pump hydro		0%	45%	14%	7%	14%
Battery storage	Lithium-ion	7%	67%	15%	11%	4%
	Sodium-ion	37%	63%	21%	16%	5%
	Lead-acid	21%	68%	21%	16%	0%
	Flow	50%	70%	20%	15%	5%
Hydrogen	Electrolysis	44%	70%	33%	22%	7%
	Fossil	25%	50%	38%	13%	13%
Demand-side response		11%	43%	21%	7%	50%
Compressed air storage		57%	57%	29%	14%	5%
Thermal storage		50%	60%	30%	10%	15%
Supercapacitor		53%	59%	24%	12%	6%
Superconducting Magnetic		67%	60%	27%	20%	7%
Flywheel		53%	63%	26%	11%	5%
Virtual power plant		21%	46%	33%	13%	33%
Vehicle-to-grid		13%	61%	39%	9%	22%
Gravity storage		62%	56%	33%	11%	11%

Demand for system flexibility is not perceived as a priority area for policy intervention. It is, however, worth noting that one expert pointed out that the need for system flexibility has not yet been fully integrated into the planning process. She explained that 'when China's power system was developed, it was dominated by highly reliable, large-scale thermal power plants…there was no need for system flexibility'.

Motivation is a priority for policy intervention for coal power flexibilisation and demand-side response. Regarding coal power flexibilisation, one expert noted that 'some coal-fired power plants can still make a profit, so there are little incentives for them to provide ancillary services'. This view was echoed by another expert who said: 'the progress of coal power flexibilisation was slow in the 13th Five-Year Plan period, and lack of capacity payment is the main reason. Some coal generators still feel that it is more profitable to provide energy to the market, but not ancillary services and capacity’. Regarding demand-side response, 50% of the survey respondents indicate that ‘motivation’ is a priority for policy intervention, probably because it is mainly influenced by consumer willingness to change their electricity-consuming behaviours.

5. Summary and policy suggestions

This section summarises the expert survey results and literature review presented in Sections 3 and 4. It also provides some key aspects that policymakers and planners may like to consider while making policy decisions.

5.1 Summary

The perceptions held by domain experts in China seem to be broadly consistent with the existing literature regarding factors that could affect the uptake of various flexibility technologies.

Technical feasibility

Several flexibility technologies, such as coal power flexibilisation, pumped hydro, lithium-ion batteries and vehicle-to-grid are mature and ready for wider adoption. Other technologies are either at the conceptualisation and proof-of-concept stages, or at an early stage of market introduction. The survey results substantiate this viewpoint: fewer than 30% of respondents indicated that flexibility technologies other than coal power, pumped hydro, lithium-ion and lead-acid batteries, and vehicle-to-grid are ready for widespread adoption.

Given China's strong engineering and research capacity and capabilities, engineering complexity and access to core patents are not perceived to be a major concern for flexibility technologies, especially coal power flexibilisation, pumped hydro, battery storage and demand-side response.

Flexibility technologies could help improve the efficiency of the electricity system by enabling higher levels of renewable energy penetration and contribute to lower CO_2 and pollutant emissions.

Existing literature suggests that coal power flexibilisation could negatively affect fuel efficiency and air pollutant control efficiency on the plant level and lead to increased wear and tear of equipment parts, caused by more frequent increase and decrease in demand (ramp-up and down) to provide load following services. Energy storage technologies, such as battery storage, pumped hydro, and particularly hydrogen storage, could also have some adverse impacts on fuel efficiency and emissions, mainly due to energy losses in the conversion process. These viewpoints were echoed by some experts participating in the survey.

For periods of long-duration seasonal variations that affect renewable sources, the study mainly considers coal power and hydrogen as potentially viable solutions. Safety concerns could limit the extent to which hydrogen usage is scaled up in the near future. Other options are being explored by researchers. For example, some thermal storage technologies, such as molten salt storage, have potential to provide long-duration storage solutions, as has been demonstrated in pilot projects.

Economic viability

With the exception of flexibilisation of existing coal power and demand-side response, other flexibility technologies – such as pumped hydro and battery storage – were considered by experts participating in the survey as less economically viable. Reasons for the experts' views include long lead times and high development costs for pumped hydro (for example, costs involved in land acquisition and infrastructure construction), rising critical mineral prices for battery storage, and high costs of electrolysers or fossil reformation equipped with CCUS for hydrogen.

Cleanliness

In the expert survey, demand-side response, vehicle-to-grid, pumped hydro, and green hydrogen were seen as the preferable technologies from the perspective of reducing GHG and air pollutant emissions.

Enabling infrastructure

One issue holding back the widespread adoption of clean hydrogen is the lack of infrastructure to transport, distribute, store and dispense hydrogen as a fuel for stationary uses. For pumped hydro, some ideal sites are found in areas far away from the existing road and transmission infrastructure, making their development expensive.

Demand-side technologies have emerged as attractive options for managing short- to medium-term variations in electricity supply and demand. Their wider adoption, however, could be affected by the lack of necessary infrastructure, such as smart meters, sensors, communication technology and the IoT. The development of this infrastructure could also be affected by the lack of standardisation and protocols for metering and information technologies, as well as public concern about data security and privacy.

Market and regulatory arrangements

Promoting the uptake of various flexibility technologies requires regulatory and market reforms to better articulate the demand for system flexibility arising from higher levels of renewable energy penetration. The need for these reforms is also highlighted by the survey results. More than 68% of the experts participating in the survey believe that market arrangements are an important influencing factor for the uptake of flexibility technologies.

5.2 Policy suggestions

Demoting coal power to a supportive role not only provides an immediate solution to the flexibility shortfalls. More importantly, it also serves as a leverage point for necessary market reforms that could pave the way for the wider adoption of clean technologies.

Emerging clean flexibility technologies, such as battery storage, green hydrogen and thermal energy storage, are not yet mature enough to be deployed at the scale considered essential for supporting further expansion of variable renewable generation in China. As these technologies begin to roll out, demoting coal power to play a supportive role in providing ancillary and capacity (not baseload) services therefore provides an attractive short-term solution. Retrofitting an existing coal power plant to provide system flexibility often takes less than three months, while it usually takes five to six years to build a pumped hydro station. However, building new coal-fired power plants purely for the purpose of peak shaving and valley filling is also less economical and it often takes up to two years to construct a 600 MW ultra-supercritical unit.

Facilitating the role change of coal power will require the introduction and optimisation of regulatory and market arrangements that would enable the uptake of other flexibility technologies when they mature. The necessary reforms include:

- introducing markets or other economic incentives for new services required to manage challenges imposed by rising renewable generation, for example, frequent ramping, increased need for reserve and a loss of inertia;
- streamlining ancillary products, such as reducing the number of products associated with a specific ancillary service, to improve market liquidity;
- extending spot markets and ancillary service markets to cover all provinces and a larger share of generation;
- better aligning ancillary service markets with the spot markets to improve the flexibility of short-term market operation, as the marketisation process deepens;

and

- introducing capacity remuneration mechanisms, e.g., capacity payments, to support backup capacity for managing seasonal variations in renewable generation, and such mechanisms should be technology-neutral or favour zero carbon technologies.

Deeper power connectivity could unlock substantial additional flexibility from existing capacity, but implementation remains a challenge.

Power connectivity envisages the creation of a fully interconnected national electricity system that allows cross-provincial and cross-regional sharing of surplus and reserve capacity facilitated by grid interconnection and coordinated market operation. Deeper power connectivity could allow more effective sharing of complementary renewable resources, especially hydro, wind and solar, that are distributed unevenly across the country, thereby reducing the need for expensive reserve and backup capacity. It could also provide increased access to a variety of supply- and demand-side options for managing variations in renewable generations. In recognition of the importance of power connectivity, the central government has recently signalled its intention to accelerate the marketisation process in the electricity sector.

In recognition of the importance of power connectivity, the National Development and Reform Commission (NDRC) and the NEA issued the Guiding Opinions on Accelerating the Establishment of a Unified National Electricity Market Reform in 2022, with particular emphasis on accelerating the marketisation process in the electricity sector. Despite this, the question of how to deepen market reform remains an issue, especially if one considers the experience of electricity market reform in China. After nearly three decades of efforts, cross-provincial and cross-regional power connectivity in China remains rather low, limited to a few centrally planned initiatives (see Appendix C).

Innovation is critical to prepare clean flexibility technologies for wider adoption, where increased R&D support is important but, in isolation, will not bring needed results.

The generation, diffusion and utilisation of novel technologies are not only shaped by technology-focused ‘hardware’ innovation processes. Indeed, they are also influenced by the dynamic interplay of actors, such as utility companies, private investors, consumers, and research institutes, and broader institutional structures, such as laws and regulations, market mechanisms, policy framework and technical norms.

A more systemic approach is, therefore, needed to support innovation in flexibility technologies.

This approach includes:

- *Demand pull via market reform and indicative planning:* Although the need for a more flexible electricity system to enable higher levels of renewable penetration is well recognised, it has not yet been clearly translated into the demand for system flexibility, due to some weaknesses in the electricity markets in China, for example, reliance on less flexible quotas for energy storage. To address these weaknesses, policymakers may consider strengthening and further expanding the spot and ancillary service markets and introducing some forms of capacity markets to better articulate the demand for system flexibility.

  Furthermore, as pointed out by some domain experts, the need for system flexibility has not yet been fully integrated into the long-term planning process in China, due to the country's reliance on large-scale thermal power plants. The situation has, however, changed in recent years, as the rapid uptake of renewable generation has created a growing demand for system flexibility to accommodate its variations.

  To clearly articulate this demand, energy planners may like to consider better integrating the need for system flexibility into the planning process. This involves first assessing the availability of flexibility resources in the existing electricity system to identify the flexibility gaps in satisfying the flexibility needs. The next step is to ascertain a least-cost set of short-term solutions to fill the gaps, including retrofitting existing coal power plants, encouraging more active demand-side responses, and better sharing of surplus and reserve capacity over larger geographical areas. After that, the system planners need to identify the need for additional flexibility capacity and translate this need into long-term indicative targets to drive investment in storage capacity and network augmentation.

- *Technology push by addressing blocking factors for bringing innovation to the market.* A central proposition in emerging innovation system studies is that some system failures or weaknesses exist that block or obstruct innovation in driving the generation, diffusion, and utilisation of novel technologies. The blocking factors may include, for example, uncertain demand for system flexibility (e.g., the absence of the market for some ancillary services), lack of industry standards (e.g., different designs of batteries used for energy storage), difficulties involved in getting access to the necessary financial resources, and misalignment between research and education priorities and the needs of industry. The importance of some of these factors is also highlighted by the survey results.

  Addressing these factors requires a multidisciplinary, portfolio policy approach that comprises a wide range of measures including, for example, R&D support, measures to mobilise sufficient investment and financing for novel technologies, standardisation measures, better information provision and knowledge sharing, and formation of early markets for novel technologies (e.g., through procurement policies).

- *Policy learning and adaptation*: The dynamic and multi-faceted nature of the innovation process highlights the importance of policy learning and adaptation. This can be considered a cycle of problem-solving attempts, which lead to learning-by-implementation through the repeated analysis of issues that emerged over the course of policy implementation and experimentation with possible solutions. To facilitate such iterative processes, monitoring and evaluating the impacts of policy mixes, as well as participatory processes of envisioning, negotiating, learning, and experimenting, are important.

Improving the flexibility of the Chinese power system requires an all-of-government approach, closely coordinating climate and supply security imperatives with other cross-cutting issues.

For example, retrofitting coal-fired power plants to enable a shift in their use from baseload capacity to supportive capacity means lower capacity utilisation rates and hence less coal burnt for power generation. Another example is electricity affordability, as the costs of system reconfiguration could put upwards pressure on the regulator to raise electricity prices, which may be viewed by the government as a potential threat to people’s living standards.

A range of available flexibility technologies can help the Chinese power system accommodate the variations renewable energy brings. However, more robust supporting policies are needed to create the conditions for clean flexibility technologies to compete against coal power. Stronger and better-designed economic incentives can help clean flexibility technologies to make a breakthrough.

Appendix A: Underlying factors for the uptake of flexibility technologies

This appendix presents key influencing factors for the uptake of various flexibility technologies considered in the report, based on a comprehensive review of studies presented in Table A-1. The information presented in this appendix forms the basis for much of the discussion in Chapter 3.

A-1 Coal power

Increased wear and tear of equipment parts: Operating a coal-fired power plant more flexibly would cause increased wear and tear on equipment and reduce the lifetime of components[18,63]. Frequent and rapid increase and decrease in demand (ramp-up and down) to provide load following services, for example, involve rapid changes in process temperature, which increase the chance of thermal fatigue, thermal expansion, fireside corrosion, rotor bore cracking, etc. These would in turn lead to increased rates of component life consumption[62]. As estimated by Agora[97], more flexible operation of a hard coal-fired power plant (50 more starts per year and a ramp rate twice as high as the baseline operation mode) would substantially increase its accumulated annual lifetime consumption from 0.4% to 3.24% (an increase by a factor of eight). This means that if the power plant has a theoretical life-time of 250 years, its life-time will fall to 31 years when operating more flexibly.

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[97] Agora (2017). Flexibility in thermal power plants. https://www.agora-energiewende.de/fileadmin/Projekte/2017/Flexibility_in_thermal_plants/115_flexibility-report-WEB.pdf.

Table A-1: Underlying influencing factors for the uptake of flexibility technologies

Flexibility technologies		Main influencing factors	Reviewed studies
Coal power		● Increased wear and tear of equipment parts and reduced lifetime of components	18, 62, 63, 97
		● Reduced fuel efficiency and higher pollutant and CO_2 emissions per unit of output	16, 63, 98
		● Carbon pricing that tends to increase the costs of coal generation	65
		● Inadequate market incentives	63, 89,99
Energy storage	Battery	● High upfront costs	23, 69-73
		● Regulatory hurdles	26, 70, 90, 94
		● Outdated market design	26, 88, 90
		● Battery recycling	26
	Pumped hydro	● Difficult to find the right site	28, 66, 100
		● Issues related to project finance	28, 67
		● Market-related issues	30, 91-93, 100
		● Lengthy regulatory process	101-106
		● Public opposition	28, 30, 100, 101, 107-109
	Hydrogen	● Storage difficulties	38, 110-112
		● High production costs	38, 113-116
		● Lack of infrastructure	38, 114, 118
		● Gaps in international standards	118,119
Demand-side response		● Lack of infrastructure	42, 81, 82, 84, 86, 87
		● Market-related barriers	82, 85-87, 120-126
		● Behavioural issues	37, 82, 85, 120, 127-131
Others	Compressed air energy storage (CAES)	● Geographical and technical constraints	47
	Supercapacitor	● Technical constraints, such as low energy density	50
	Thermal storage	● Lack of technological readiness for commercial deployment, except molten-salts storage coupled with CSP plants	53
	Vehicle-to-grid	● Lack of economic unviability,	59-61

	(V2G)	mainly due to battery degradation caused by more frequent charging/discharging	
	Virtual power plant (VPP)	● Inability of existing VPP models to account for the complexity of an increasingly decentralised power system	56
		● The practicality of proposed VPP models rarely being rested by real world applications	57

Reduced fuel efficiency: Running the plant at low load would reduce fuel efficiency, leading to higher CO_2 and pollutant emissions per unit of output[63]. High-resolution operation data obtained from two typical coal power units (300 MW and 600 MW) in China is used to analyse the emissions impact of coal power flexibilisation. The results suggest that deep cycling operation (i.e., operating the power plant at much lower loads than the minimum) would substantially increase the emissions factors: 11.3%~17.5% for $CO_{2,}$ 10.2%~108.4% for NO_x, and 41% for dust[6]. Based on a case study of Northern Ireland, the benefits of emissions reduction from reduced wind curtailments enabled by more flexible operation of coal-fired power plants could be offset by reduced fuel efficiency and higher emissions per unit of output[98]. It also showed that co-firing with low-emissions fuels during periods of high wind generation could help address this issue.

Carbon pricing: Carbon pricing can increase the costs of coal generation and hence discourage the use of coal power generation for providing system flexibility. A scenario analysis suggests that strict targets for CO_2 emissions reduction would significantly reduce the scope for coal power to provide system flexibility, where only coal-fired power plants with carbon capture and storage facility or co-firing of biomass are of relevance[65].

Inadequate market incentives: In energy only markets, higher penetration levels of low-cost renewable generation and, in some cases priority despatch, have depressed wholesale electricity prices. More volatile and low electricity prices have provided limited incentives for utility companies to enhance the flexibility of their conventional thermal power plants, including coal-fired ones. Indeed, some of them have found it difficult to cover the fixed and operating costs of their thermal power plants[89, 99]. This issue gets compounded by the under-development of ancillary service markets that provide insufficient remuneration for conventional power plants to meet the rising demand for system flexibility fuelled by higher levels of renewable generation[63].

A-2 Battery storage

High upfront costs: Despite the significant cost reductions of several battery technologies, the upfront costs for deploying battery storage systems remain high, especially when compared with more mature technologies, such as pumped hydro[23, 69-71]. The recent surge in raw material and battery component prices has further accentuated this challenge

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[98] Kubik, M. L., Coker, P. J., Barlow, J. F. (2015). Increasing thermal plant flexibility in a high renewables power system. *Applied Energy*, 154, 102-111.

[99] Hogan, M. (2017). Follow the missing money: Ensuring reliability at least cost to consumers in the transition to a low-carbon power system. *The Electricity Journal*, 30(1), 55-61.

because lithium-ion battery prices rose in 2022 after more than a decade of decline since 2010[71]. The upfront costs for second-life battery storage systems are lower (about 20% to 35%) than new systems, but their adoption could be affected by high life-cycle costs, due to factors, such as high repurposing costs (e.g., costs involved in the procurement, collection, and shipment of retired mobility batteries), less operating life, lower depth of discharge, and high electricity prices[69,72].

Regulatory hurdles: The existing literature has identified a range of regulatory issues that could impede the deployment of battery storage in the power system. They include, for example, administrative delays caused by regulatory complexity[70], the treatment of batter storage as generation assets that precludes its application for transmission and distribution investment deferral (using storage to manage bottlenecks in the grids), as network companies are not allowed to own storage assets[26], unclear classification of battery storage as a eligible participant in ancillary and balancing services markets[90], and charging grid fees on battery storage[94].

Outdated market design: It is noted in several studies that the design of the electricity markets has been outdated in some countries and (hence) presented a major impediment to the deployment of battery storage[26, 90]. One particular issue is the absence or underdevelopment of the markets for procuring some ancillary services that provide insufficient remuneration to battery storage providers. Another issue is outdated market rules that make it difficult for battery storage providers to participate in the capacity and ancillary service markets. In the United Kingdom, for example, battery storage projects only secured 15% of the capacity auctioned for actual delivery between 2020 and 2035. This is mainly because battery storage providers were not allowed to participate in the capacity auctions if their capacity is less than 2 MW, unless they bid into the market alongside other generators through an aggregation service. In addition, capacity providers are often required to deliver a certain amount of electricity at any time during the contracted period when the system is under stress. This is a key impending issue for battery storage providers as they must remain fully charged for a long period and suffer parasitic energy losses. If not, they may not be able to fulfil their contract commitments and will be subject to heavy penalties[88].

Battery recycling: The uptake of battery storage presents a serious waste-treatment challenge, as mounting numbers of waste batteries, if not treated properly, would release heavy metals and toxic chemicals into the natural environment, causing soil contamination and water pollution[26].

A-3 Pumped hydro

Difficult to find an appropriate site: Choosing an appropriate location for pumped hydro development required identifying a site with the desired landscape topography (head and slope) and a location close to road and transmission infrastructure. A favourable landscape topography provides the technically required head difference and slope between the two reservoirs of pumped hydro storage. Artificially developing the required head and slope would result in increased construction times and costs[66]. The ideal sites for pumped hydro are sometimes found in areas that are designated as reserves or have high socio-cultural value. Land acquisition, therefore, becomes a main barrier for their development[100]. Some sites are also far away from the existing road and transmission infrastructure, making development expensive[28].

Project finance: Long lead times, high development costs (e.g., capital costs, costs involved in land acquisition and infrastructure construction), and long payback periods are often cited as major barriers to pump hydro projects, as they tend to put upwards pressure on making project financing a challenging task[28,67].

Market-related issues: It is often cited in the literature that the ancillary services and capacity provided by pumped hydro are not adequately remunerated in some electricity markets, due to factors such as the lack of a well-established market for ancillary services, no time-of-use tariffs that could enable access to low-cost electricity for pumping water back to refill the upper reservoirs during off-peak periods[91-93], grid charges for electricity consumed for pumping, water fees for pumped hydro projects using a river or lake as lower reservoirs[100], and insufficient carbon pricing that favours gas as peak shaver[30]. These factors pose major barriers for the uptake of pumped hydro.

Lengthy regulatory process: The lengthy approval process is cited as one of the main barriers for pumped hydro development in some countries and regions. In the United States, for example, any non-federal pumped hydro projects need to obtain regulatory permits from the Federal Energy Regulatory Commission (FERC) and several state agencies. This process may take three to five years, or even longer before the developer has the authority to start the construction. The construction times are often in the range of three to five years, suggesting that when funding is first committed at the project approval stage, it may not see returns for more than six years[101]. Extensive delays in obtaining

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[100] Steffen, B. (2012). Prospects for pumped-hydro storage in Germany. *Energy Policy*, 45, 420-429.

[101] NHA (2014), Challenges and opportunities for new pumped storage development. https://www.hydro.org/wp-content/uploads/2017/08/NHA_PumpedStorage_071212b1.pdf.

regulatory permits for pumped hydro projects are also documented in Australia[102] and Nepal[103]. Lack of coordination across various regulatory bodies involved in the governance of pumped hydro projects, and the absence of a legal framework for governing the permitting process are the main causes for the delays in the project approval process[103,104,105,106].

Public opposition: Pumped hydro is reportedly opposed by the public for a variety of reasons, including the environmental impacts associated with a pumped hydro project[30,101,107]. This is especially true for open-loop projects; these projects are connected to naturally flowing bodies of water as lower reservoirs and hence often have greater aquatic and terrestrial impacts[108]. In contrast, the reservoirs for closed-loop projects are typically located in areas that are physically separated from existing river systems, thereby posing less aquatic impacts[101]. Other reasons include, for example, resident relocation[28], 'not in my backyard' sentiments[100], concerns about local impact (e.g., bad smells from stagnant water, prolonged construction time, risk of bursting during earthquakes) of a pumped hydro project[105], and competing use for water (for example, agriculture and town water supply)[109].

A-4 Hydrogen

Storage difficulties. Hydrogen is relatively difficult to store when compared with fossil fuel, mainly due to its low density. It requires more space and larger storage: 3-4 times

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[102] Macdonald, I., Rowland, C. (2022) Tunnel vision: Women, mining and communities. https://www.oxfam.org.au/wp-content/uploads/2011/11/OAus-TunnelVisionWomenMining-1102.pdf.

[103] Ghimire, L. P., Kim, Y. (2018). An analysis on barriers to renewable energy development in the context of Nepal using AHP. *Renewable Energy*, 129, 446-456.

[104] Provis, E. L. (2019). Pumped-hydro in Bendigo: Room for wider reform?. *The Electricity Journal*, 32(8), 106634.

[105] Sovacool, B. K., Dhakal, S., Gippner, O., Bambawale, M. J. (2011). Halting hydro: A review of the socio-technical barriers to hydroelectric power plants in Nepal. *Energy*, 36(5), 3468-3476.

[106] Deane, J. P., Gallachóir, B. Ó., McKeogh, E. J. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. *Renewable and Sustainable Energy Reviews*, 14(4), 1293-1302.

[107] Yang, C. J., Jackson, R. B. (2011). Opportunities and barriers to pumped-hydro energy storage in the United States. *Renewable and Sustainable Energy Reviews*, 15(1), 839-844.

[108] US Pacific Northwest National Laboratory (2020). A comparison of the environmental effects of open-loop and closed-loop pumped storage hydropower. https://www.energy.gov/sites/prod/files/2020/04/f73/comparison-of-environmental-effects-open-loop-closed-loop-psh-1.pdf.

[109] Pérez-Díaz, J. I., Chazarra, M., García-González, J., and others (2015). Trends and challenges in the operation of pumped-storage hydropower plants. *Renewable and Sustainable Energy Reviews*, 44, 767-784.

more storage infrastructure than natural gas, according to a Bloomberg NEF report[110]. Besides, some storage technologies, such as salt cavern storage, can only be deployed under certain geographical conditions. Another issue with hydrogen storage is the lack of practical experience in project development, leading to long lead times[38]. It is reported that a renewable-based hydrogen project in Oman will take around ten years to become fully operational[111]. A similar project is reported to take four to six years to complete in Australia[112].

High production costs. Globally, the production costs of green hydrogen are high when compared with fossil-based hydrogen. According to IEA, the average costs of hydrogen production from natural gas are $1.0-2.5/kg without CCUS and $1.5-3.0/kg with CCUS. The average cost of renewable-based hydrogen is $4.0-9.0/kg[38]. A range of factors, such as low technical readiness, the use of precious metal (*e.g.,* iridium and platinum used in electrolysers) in production and storage facilities, and high installation costs, are found to be responsible for the high fixed costs of hydrogen projects[113,114,115,116,117]. The recent surge in natural gas and oil prices is likely to improve the competitiveness of renewable-based hydrogen. According to the IEA, the costs of offshore wind-based hydrogen in Europe and solar-based hydrogen in the Middle East and China would become cheaper than natural gas-based hydrogen, when the gas prices go over $25/MMBtu (Million Btu)[38].

Lack of hydrogen infrastructure. Hydrogen trade could be hindered by the lack of

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[110] Bloomberg NEF (2020). Hydrogen Economy Outlook 2020. https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf.

[111] L. Paddison (2021). Oman plans to build world’s largest green hydrogen plant, Guard. https://www.theguardian.com/world/2021/may/27/oman-plans-to-build-worlds-largest-green-hydrogen-plant.

[112] AREA (2022). Australia’s first large scale hydrogen plant to be built in Pilbara. https://arena.gov.au/news/australias-first-large-scale-hydrogen-plant-to-be-built-in-pilbara/

[113] Parra, D., Valverde, L., Pino, F. J., Patel, M. K. (2019). A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. *Renewable and Sustainable Energy Reviews*, 101, 279-294.

[114] Ren, X., Dong, L., Xu, D., Hu, B. (2020). Challenges towards hydrogen economy in China. *International Journal of Hydrogen Energy*, 45(59), 34326-34345.

[115] Colella, W. G., James, B. D., Moton, J. M., Saur, G., Ramsden, T. (2014). Techno-economic analysis of PEM electrolysis for hydrogen production. In *Electrolytic Hydrogen Production Workshop*. Golden, CO: NREL.

[116] Ammermann, H., Hoff, P., Atanasiu, M., Tisler, O., Kaufmann, M. (2015). Advancing Europe's Energy Systems-Stationary Fuel Cells in Distributed Generation. https://op.europa.eu/en/publication-detail/-/publication/19f1ad71-303c-47fa-a292-90f85643bd2a.

[117] Agarwal, R. (2022). Transition to a Hydrogen-Based Economy: Possibilities and Challenges. *Sustainability*, 14(23), 15975.

pipeline and shipping infrastructure[114,118]. Repurposing natural gas pipelines for hydrogen transportation can reduce investment costs by 50-80%, when compared with building new pipelines[38]. Nevertheless, limited practical experience would be the main barrier to implementing this strategy.

Gaps in international standards. Existing standards on emissions accounting are often limited to CO_2 and methane (fugitive) emissions are overlooked[119]. Another issue is the lack of technical standards on hydrogen technologies (e.g., electrolysers) to ensure the safety and quality of hydrogen production[118].

A-5 Demand-side response

Lack of infrastructure: For more active demand-side response to take place, enabling infrastructure such as smart meters, sensors, communication technology, IoT, is required to automatically monitor and control electricity-consuming activities at the demand-side, rather than simply relying on manual efforts made by the consumers, such as dimming lights, and shutting off equipment[81,82]. The development of this infrastructure may, however, be affected by a wide range of factors including, for example, the lack of standardisation and protocols for metering and ICT technologies[82,83], insufficient readiness of some technologies (for example, ICT-based demand-side management tools) integral to more active demand-side response[84], concerns about data security and privacy[85], and large investments required to deploy more sophisticated technologies[42,86,87].

Market-related barriers: Demand-side response has mainly been used for the provision of emergency contingency support, with limited participation in the capacity and ancillary service markets. Existing literature has identified various market-related barriers responsible for this phenomenon. One such barrier is about market rules. Although demand-side response providers are allowed to participate in some electricity markets to provide ancillary services, they are only minor players with small market shares, mainly due to market rules that limit the possible scale of demand-side participation[120]. For example, the bulk power system product definitions, that are related to how regional reliability councils in the United States choose to define ancillary service, often explicitly

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[118] IEA (2019). The future of hydrogen. https://www.iea.org/reports/the-future-of-hydrogen.

[119] Howarth, R. W., Jacobson, M. Z. (2021). How green is blue hydrogen?. *Energy Science & Engineering*, 9(10), 1676-1687.

[120] Nolan, S., O'Malley, M. (2015). Challenges and barriers to demand response deployment and evaluation. *Applied Energy*, 152, 1-10.

preclude some demand-side providers from participating in the electricity markets[86,121]. The California ISO requires an ancillary service provider to be able to maintain its capacity for a specified period of time, otherwise it will not be allowed to participate in the ancillary service markets. This potentially precludes some demand-side response providers who cannot fulfill this requirement[120]. Some technical requirements (e.g., minimum resource size, telemetry) contained in the bulk power system product definition also create barriers for demand-side response providers to participate in the ancillary service markets[85,86].

Lack of capacity payments is another barrier for demand-side response in the electricity markets. Demand-side response is widely considered as cost-effective in providing capacity by reducing the electricity-consuming activities during peak-demand periods, mainly because it could alleviate the need for additional investment in expensive peaking power plants that will be sitting idle for long periods[122]. Some forms of capacity payments are required to incentivise investments in demand-side response. As estimated by Hurley and others[123], over 90% of the revenue earned by demand-side response providers is from the capacity market, underscoring the importance of the capacity payments for attracting investments in demand-side response.

Other market-related barriers include, for example, the absence of time-of-use pricing and real-time information to encourage energy-saving behaviours[87], information and transaction costs incurred by participation in the markets (e.g., costs related to information searching, and contract negotiation and enforcement), under-valuation of flexibility in an electricity system[82], insufficient attention to encourage aggregated response from the demand-side (e.g., demand-response from residential consumers via an aggregator) in the electricity markets[124], learning costs for the system operators to better manage the

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[121] Ma, O., Alkadi, N., Cappers, P., and others(2013). Demand response for ancillary services. *IEEE Transactions on Smart Grid*, 4(4), 1988-1995.

[122] Cutter, E., Woo, C. K., Kahrl, F., Taylor, A. (2012). Maximizing the value of responsive load. *The Electricity Journal*, 25(7), 6-16.

[123] Hurley, D., Peterson, P., Whited, M. (2013). Demand response as a power system resource. Synapse Energy Economics Inc., https://www.synapse-energy.com/sites/default/files/SynapseReport.2013-03.RAP_.US-Demand-Response.12-080.pdf.

[124] Koliou, E., Eid, C., Chaves-Ávila, J. P., Hakvoort, R. A. (2014). Demand response in liberalized electricity markets: Analysis of aggregated load participation in the German balancing mechanism. *Energy*, 71, 245-254.

provision of flexibility services (*e.g.,* frequency-regulation services) by the demand-side[125], and incumbent effects that tend to reduce the scope and scale of demand-side participation in providing system flexibility[126].

Behavioural issues: Consumer willingness to provide demand-side response can be affected by the technical and market barriers, but they could also be seen as a barrier in themselves. Consumer participation in demand-side response is limited by high information and transaction costs, both real and perceived[82]. Information costs refer to the opportunity costs of the time taken in searching for information in understanding the benefits and costs of demand-side response. How high these costs are is dependent on several factors, such as, *a priori* knowledge, education, and public information availability. Transaction costs are related to costs incurred by participation in demand-side response, such as contract negotiations[127].

Besides information and transaction costs, other key behavioural issues impeding demand-side response include complexity aversion that tends to encourage non-energy-intensive small commercial and residential consumers to disengage in demand-side response, due to their complex internal decision-making processes and bounded rationality[44], inconvenience and loss of comfort caused by demand-side response[85,120], uncertainty about potential revenue and costs of participation in demand-side response[128], status quo bias and behavioural inertia[129,130], and the level of trustworthy and credibility of the relevant parties involved in a demand-side response programme[131].

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[125] Borne, O., Korte, K., Perez, Y., and others (2018). Barriers to entry in frequency-regulation services markets: Review of the status quo and options for improvements. *Renewable and Sustainable Energy Reviews*, 81, 605-614.

[126] Lockwood, M., Mitchell, C., Hoggett, R. (2020). Incumbent lobbying as a barrier to forward-looking regulation: The case of demand-side response in the GB capacity market for electricity. *Energy Policy*, 140, 111426.

[127] Yang, M., Chi, Y., Mamaril, K., and others (2020). Communication-based approach for promoting energy consumer switching: Some evidence from Ofgem's database trials in the United Kingdom. *Energies*, 13(19), 5179.

[128] Balcombe, P., Rigby, D., Azapagic, A. (2014). Investigating the importance of motivations and barriers related to microgeneration uptake in the UK. *Applied Energy*, 130, 403-418.

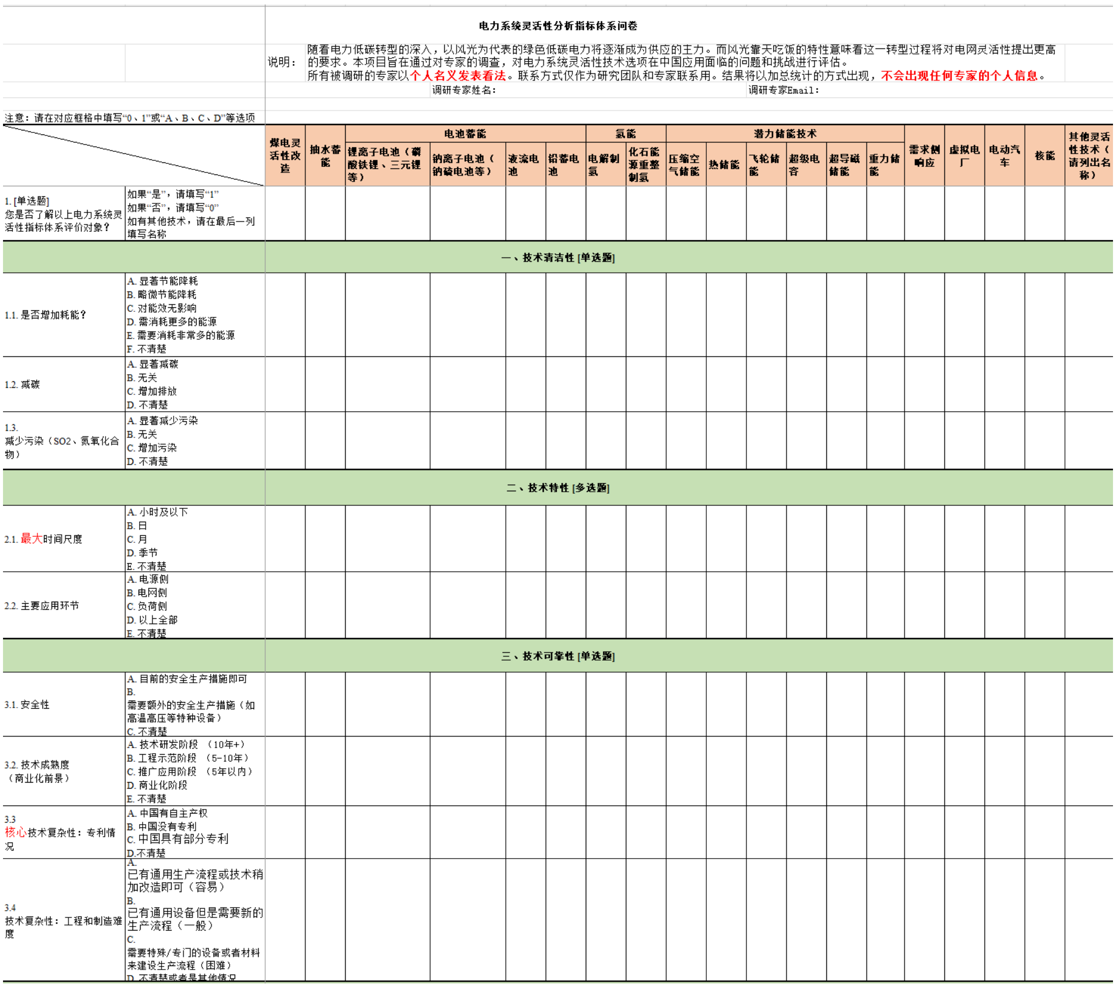
[129] Nilsson, A., Bergstad, C. J., Thuvander, L., and others (2014). Effects of continuous feedback on households' electricity consumption: Potentials and barriers. *Applied Energy*, 122, 17-23.

[130] Balta-Ozkan, N., Davidson, R., Bicket, M., Whitmarsh, L. (2013). Social barriers to the adoption of smart homes. *Energy Policy*, 63, 363-374.

[131] Darby, S. J., McKenna, E. (2012). Social implications of residential demand response in cool temperate climates. *Energy Policy*, 49, 759-769.

Appendix B: Questionnaire

Thirty eight experts were selected to answer the questionnaire. The experts who responded were from public agencies, industry associations, utility companies, research institutes, universities, governmental departments and NGOs that have actively engaged in the electricity sector in China. Some experts were also interviewed for further discussion.



电力系统灵活性分析指标体系问卷

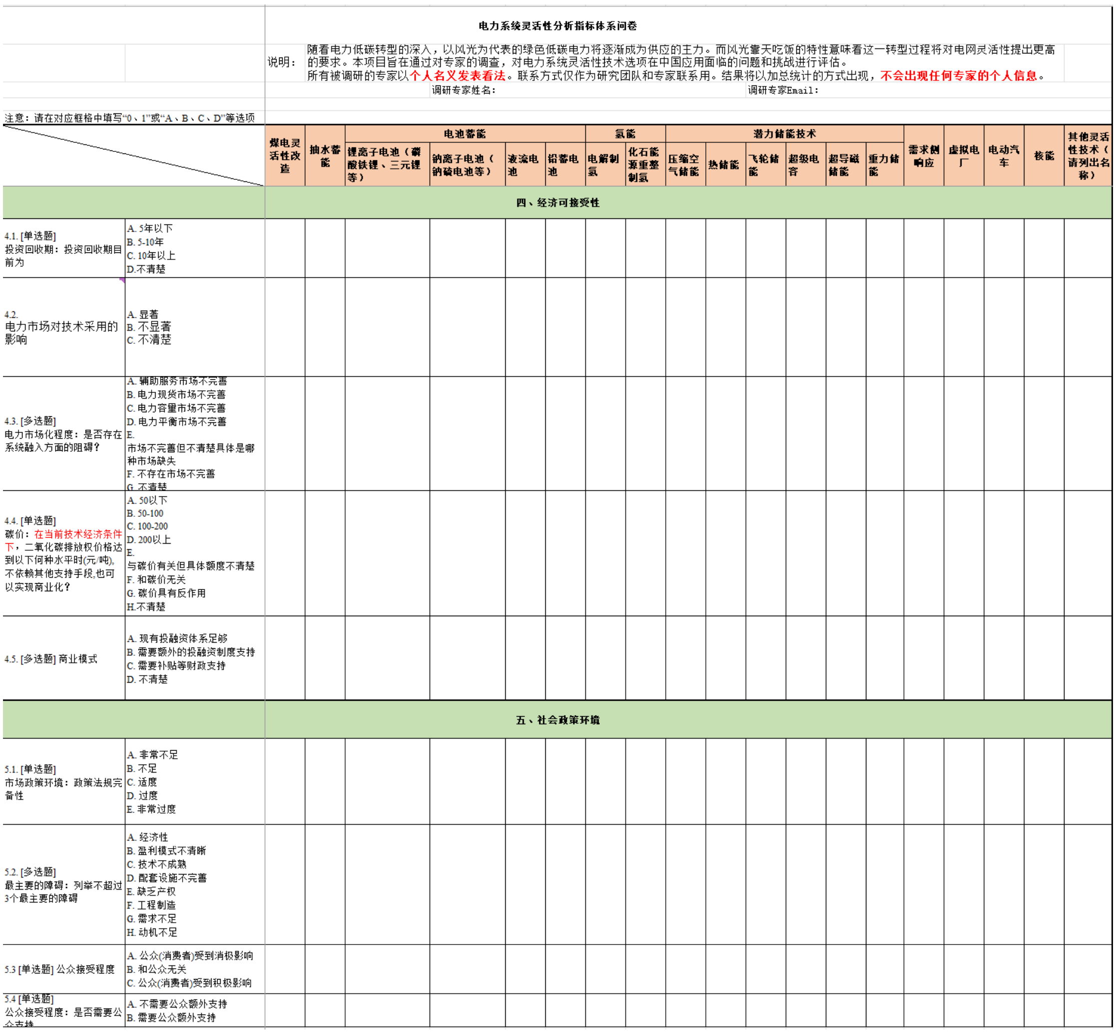
说明： 随着电力低碳转型的深入，以风光为代表的绿色低碳电力将逐渐成为供应的主力。而风光靠天吃饭的特性意味着这一转型过程将对电网灵活性提出更高的要求。本项目旨在通过对专家的调查，对电力系统灵活性技术选项在中国应用面临的问题和挑战进行评估。
所有被调研的专家以**个人名义发表看法**。联系方式仅作为研究团队和专家联系用。结果将以加总统计的方式出现，**不会出现任何专家的个人信息**。

调研专家姓名：

调研专家Email：

注意：请在对应框格中填写“0、1”或“A、B、C、D”等选项

				电池蓄能				氢能		潜力储能技术										
		煤电灵活性改造	**抽水蓄能**	**锂离子电池（磷酸铁锂、三元锂等）**	**钠离子电池（钠硫电池等）**	**液流电池**	**铅蓄电池**	**电解制氢**	**化石能源重整制氢**	**压缩空气储能**	**热储能**	**飞轮储能**	**超级电容**	**超导磁储能**	**重力储能**	**需求侧响应**	**虚拟电厂**	**电动汽车**	**核能**	**其他灵活性技术（请列出名称）**
1. [单选题] 您是否了解以上电力系统灵活性指标体系评价对象？	如果“是”，请填写“1” 如果“否”，请填写“0” 如有其他技术，请在最后一列填写名称																			
		一、技术清洁性 [单选题]																		
1.1. 是否增加耗能？	A. 显著节能降耗 B. 略微节能降耗 C. 对能效无影响 D. 需消耗更多的能源 E. 需要消耗非常多的能源 F. 不清楚																			
1.2. 减碳	A. 显著减碳 B. 无关 C. 增加排放 D. 不清楚																			
1.3. 减少污染（SO2、氮氧化合物）	A. 显著减少污染 B. 无关 C. 增加污染 D. 不清楚																			
		二、技术特性 [多选题]																		
2.1. 最大时间尺度	A. 小时及以下 B. 日 C. 月 D. 季节 E. 不清楚																			
2.2. 主要应用环节	A. 电源侧 B. 电网侧 C. 负荷侧 D. 以上全部 E. 不清楚																			
		三、技术可靠性 [单选题]																		
3.1. 安全性	A. 目前的安全生产措施即可 B. 需要额外的安全生产措施（如高温高压等特种设备） C. 不清楚																			
3.2. 技术成熟度（商业化前景）	A. 技术研发阶段 （10年+） B. 工程示范阶段 （5-10年） C. 推广应用阶段 （5年以内） D. 商业化阶段 E. 不清楚																			
3.3 核心技术复杂性：专利情况	A. 中国有自主产权 B. 中国没有专利 C. 中国具有部分专利 D.不清楚																			
3.4 技术复杂性：工程和制造难度	A. 已有通用生产流程或技术稍加改造即可（容易） B. 已有通用设备但是需要新的生产流程（一般） C. 需要特殊/专门的设备或者材料来建设生产流程（困难） D. 不清楚或者是其他情况																			



电力系统灵活性分析指标体系问卷

说明：随着电力低碳转型的深入，以风光为代表的绿色低碳电力将逐渐成为供应的主力。而风光靠天吃饭的特性意味着这一转型过程将对电网灵活性提出更高的要求。本项目旨在通过对专家的调查，对电力系统灵活性技术选项在中国应用面临的问题和挑战进行评估。
所有被调研的专家以个人名义发表看法。联系方式仅作为研究团队和专家联系用。结果将以加总统计的方式出现，不会出现任何专家的个人信息。

调研专家姓名：

调研专家Email：

注意：请在对应框格中填写“0、1”或“A、B、C、D”等选项

		煤电灵活性改造	抽水蓄能	电池蓄能				氢能		潜力储能技术						需求侧响应	虚拟电厂	电动汽车	核能	其他灵活性技术（请列出名称）
				锂离子电池（磷酸铁锂、三元锂等）	钠离子电池（钠硫电池等）	液流电池	铅蓄电池	电解制氢	化石能源重整制氢	压缩空气储能	热储能	飞轮储能	超级电容	超导磁储能	重力储能					
		四、经济可接受性																		
4.1. [单选题] 投资回收期：投资回收期目前为	A. 5年以下 B. 5-10年 C. 10年以上 D.不清楚																			
4.2. 电力市场对技术采用的影响	A. 显著 B. 不显著 C. 不清楚																			
4.3. [多选题] 电力市场化程度：是否存在系统融入方面的阻碍？	A. 辅助服务市场不完善 B. 电力现货市场不完善 C. 电力容量市场不完善 D. 电力平衡市场不完善 E. 市场不完善但不清楚具体是哪种市场缺失 F. 不存在市场不完善 G. 不清楚																			
4.4. [单选题] 碳价：在当前技术经济条件下，二氧化碳排放权价格达到以下何种水平时(元/吨)，不依赖其他支持手段，也可以实现商业化？	A. 50以下 B. 50-100 C. 100-200 D. 200以上 E. 与碳价有关但具体额度不清楚 F. 和碳价无关 G. 碳价具有反作用 H.不清楚																			
4.5. [多选题] 商业模式	A. 现有投融资体系足够 B. 需要额外的投融资制度支持 C. 需要补贴等财政支持 D. 不清楚																			
		五、社会政策环境																		
5.1. [单选题] 市场政策环境：政策法规完备性	A. 非常不足 B. 不足 C. 适度 D. 过度 E. 非常过度																			
5.2. [多选题] 最主要的障碍：列举不超过3个最主要的障碍	A. 经济性 B. 盈利模式不清晰 C. 技术不成熟 D. 配套设施不完善 E. 缺乏产权 F. 工程制造 G. 需求不足 H. 动机不足																			
5.3 [单选题] 公众接受程度	A. 公众(消费者)受到消极影响 B. 和公众无关 C. 公众(消费者)受到积极影响																			
5.4 [单选题] 公众接受程度：是否需要公众支持	A. 不需要公众额外支持 B. 需要公众额外支持																			

https://docs.google.com/spreadsheets/d/1cX8BTi4qh-GZIBPvf4Lfwq2BIsonmvyOdGpfqaV6dFw/edit#gid=1246422013

Appendix C: A brief overview of electricity market reform in China

The electricity industry was historically considered by the Chinese government to be an important tool to serve wider development objectives of promoting rapid economic growth and improved living standards. The electricity industry was identified as strategically important, and remained in public control[132]. The early 1980s saw rising electricity demand, driven by rapid economic growth and the central government was unable to provide required investments to satisfy demand. The result was power shortages throughout the country. Between 1984 and 1993, for example, electricity production in China fell short of demand by about 20%[133]. Chronic power shortages created a bottleneck for economic and social development. In response, in 1985, the central government issued the Provisional Regulation on Promoting Fund-Raising for Investment in the Power Sector and Implementing Different Power Prices. This regulation terminated the exclusive rights of the central government to invest in the electricity industry, and allowed other investors (especially, local governments) to invest in the generation sector; this was consistent with the intention of retaining public control of the industry as noted above[134].

Further efforts were made to deepen market reform in 2002, with the release of a policy document known as the 'Document No.5'. The State Power Corporation (SPC) was unbundled and its generation assets were assigned into five generation companies (the 'big five') and its transmission and distribution assets were allocated into two grid companies, namely, the State Grid company, and South China Grid company[135]. But these efforts were stifled in 2003 when severe power shortages afflicted the country. In 2004, 25 of China's 31 provinces and major municipalities sustained significant power losses. The power deficit was estimated to be 10% of installed capacity. Industry experienced forced closures and consequential economic losses; and households felt the impact of a

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[132] Zweig, D. (2019) China's Political Economy. In *Politics in China: An introduction*. Joseph, W. A. (Ed.). Oxford University Press, USA.

[133] Li, B., Dorian, J. P. (1995). Change in China's power sector. *Energy Policy*, 23(7), 619-626.

[134] Yeoh, B. S., Rajaraman, R. (2004). Electricity in China: the latest reforms. *The Electricity Journal*, 17(3), 60-69.

[135] Xu, S., Chen, W. (2006). The reform of the electricity power sector in the PR of China. *Energy Policy*, 34(16), 2455-2465.

significant reduction in basic comfort levels. The Chinese government felt that their main priority for the electricity industry – sufficient power supply to support economic growth and living standards – was threatened. They immediately put market reforms on halt and shifted to encouraging investments in new power projects[136].

In 2015, the Central Committee of the Communist Party of China and the State Council jointly issued the Several Opinions on Further Deepening Power Sector Reform, aimed at improving the efficiency of electricity supply, mainly through the establishment of a 'fair, normative, efficient, competitive, open-access, and non-discriminative' market for electricity trading[137]. In 2022, the central government signalled its intention to deepen market reform, to create a unified national market for electricity.

Cross-province trade in electricity has increased substantially in China since the mid-2010s, from less than 100 TWh in 2006, to over 480 TWh in 2018[138]. This is comparable to the world's tenth largest electricity consumer, France. In 2021, interregional and interprovincial electricity trade in the Beijing Power Exchange Centre registered a 7.3% year-on-year increase, reaching 1,240 TWh. The same year also witnessed record growth in interregional and interprovincial electricity trade in the Guangzhou Power Exchange Centre, which rose to 67 TWh, a more than 90% increase from the previous year[139].

Despite this growth, substantial differences in the market arrangements across provincial electricity exchange centres, lack of cross-province coordination in system operation, and insufficient network infrastructure are still restricting further progress toward interregional and interprovincial electricity trade in China. Most interregional and interprovincial electricity trade has been conducted based on long-term plans or deals made directly between provincial governments. Local system operators often take the yearly interregional and interprovincial trading plans proposed by the State Grid Company as mandatory, though it is supposed to be an indicative guideline. In 2022, when hydro-rich

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[136] Wang, Q., Chen, X. (2012). China's electricity market-oriented reform: from an absolute to a relative monopoly. *Energy Policy*, 51, 143-148.

[137] Guo, H., Davidson, M. R., Chen, Q., and others (2020). Power market reform in China: Motivations, progress, and recommendations. *Energy Policy*, 145, 111717.

[138] Li, W., Yang, M., Long, R., and others (2021). Assessment of greenhouse gasses and air pollutant emissions embodied in cross-province electricity trade in China. *Resources, Conservation and Recycling*, 171, 105623.

[139] Sun, N., Guo, A., Lin, L. (2022). Status and trends: A bird's eye view of the Chines electricity market. https://www.dentons.com/en/insights/articles/2022/april/21/status-and-trends-a-bird-s-eye-view-of-the-chinese-electricity-market.

province Sichuan was hit by a major supply shortfall because of less-than-expected rainfall, it still exported some electricity to north China to fulfill the interregional trading plans.

Deepening power connectivity is a complex process. Progress cannot be simply made by treating electricity as a tradeable market commodity and then facilitating trade through normal market mechanisms (e.g., through financial equivalents of the physical electricity market). Or by taking the electricity industry outside the purview of the public sector through, for example, privatisation and independent regulation, to remove the opposition to market reform. The slow progress of electricity market reform in China, as selectively discussed above, should provide some credence to this viewpoint. By implication, this also suggests that power connectivity cannot be considered an immediate solution to addressing the flexibility shortfalls in China's electricity system.

Abbreviations

CAES: compressed air energy storage

CCUS: carbon capture, utilisation, and storage

CO_2: carbon dioxide

CREA: Centre for Research on Energy and Clean Air

CSP: concentrated solar power

EVs: electric vehicles

GHG: greenhouse gas

ICT: information and communication technology

IEA: International Energy Agency

IHA: International Hydropower Association

IoT: Internet of Things

IPCC: Intergovernmental Panel on Climate Change

NDRC: National Development and Reform Commission (China)

NGO: non-governmental organisations

NEA: National Energy Administration (China)

V2G: Vehicle-to-grid

VPP: virtual power plant