INTERNATIONAL CENTRE FOR SUSTAINABLE CARBON

CIAB

EXECUTIVE SUMMARY
JANUARY 2024

MAINTAINING A STABLE ELECTRICITY GRID IN THE ENERGY TRANSITION

THE ELECTRICITY GRID NETWORK IS ESSENTIAL FOR EVERYTHING WE DO. ENSURING SECURE, DEPENDABLE AND AFFORDABLE ELECTRICITY SUPPLY IS A PRIORITY

The modern world relies on access to affordable, dependable power, delivered by a secure and robust electricity grid network. There is almost a total reliance on electricity grids to support systems, processes, data management, communications, healthcare, supply chains as well as essential services such as water and food supply management. Anything which affects the ability of grids to deliver power on a reliable and secure basis, at a reasonable cost, risks societal and economic disruption. Electric power grids have been carefully managed, monitored, and governed by stringent regulations and operational practices refined over many years. They have evolved over more than a century and traditionally been based on large, dispatchable point power generation sources. There are more than 80 million km of grid network globally and this is expanding by 2.3 million km/y (IEA, 2023d) with repair, replacement and upgrade required in addition to expansion.

Electricity supply and demand must always be balanced. System stability requires constant equilibrium between power generation and consumption, even as demand fluctuates. Grids operate within a protected narrow frequency band. When demand exceeds supply, such as when a power plant fails, the associated drop in system frequency can result in widespread problems, if not managed appropriately. Therefore, if system frequency is not restored within a limited time window (typically nine minutes) existing power plants operational on the system can enter controlled shutdown as a protection mechanism. If system frequency falls further, system collapse may occur, with associated loss of energy to the entire system. During Storm Uri in 2021, the Texas grid, operated by the Electric Reliability Council of Texas (ERCOT), came within ‘four minutes thirty-seven seconds from a total collapse’ which would have resulted in a state-wide blackout of their 90 GW peak system. Almost half its power generation was lost, narrowly avoiding catastrophic impact on the region and its population, which would have taken weeks to restore. As it was, there was power failure to five million people with a further 11 million impacted by power interruptions. There were 246 attributed deaths and an economic impact of around $200 billion. Texas is far from being an isolated case of significant blackout with examples in Argentina, Bangladesh, India, South Australia and the UK.

The approaches being taken to reduce power sector emissions in line with the Paris Agreement, specifically, the addition of variable renewable energy (VRE), mainly wind and solar, are transforming electric power grids while they are being relied on more. Demand is growing with increasing electrification, and the share of VRE feeding into the grid is expanding. Correspondingly, as the deployment of VRE technologies increases, large dispatchable generating capacity, used to support and back up the intermittency of VRE, is being phased out. New VRE capacity being installed are smaller units, greater in number to facilitate a level of bulk load, and often located in remote areas, both on-land and offshore. Deployment of more VRE based generating capacity and the associated intermittent nature of power generation (being exposed to the vagaries of the weather) plus the age of much of the grid, extreme weather events, and system congestion, mean that considerable investment is required for the upgrading and expansion of electricity grids. Such investment and expansion are not keeping pace with VRE deployment and dispatchable power capacity phase out, with associated risk to sensitive supply demand management needs.

The less predictable nature of VRE makes it harder to continuously match electricity supply and demand. The more VRE on the system, the larger the challenge.

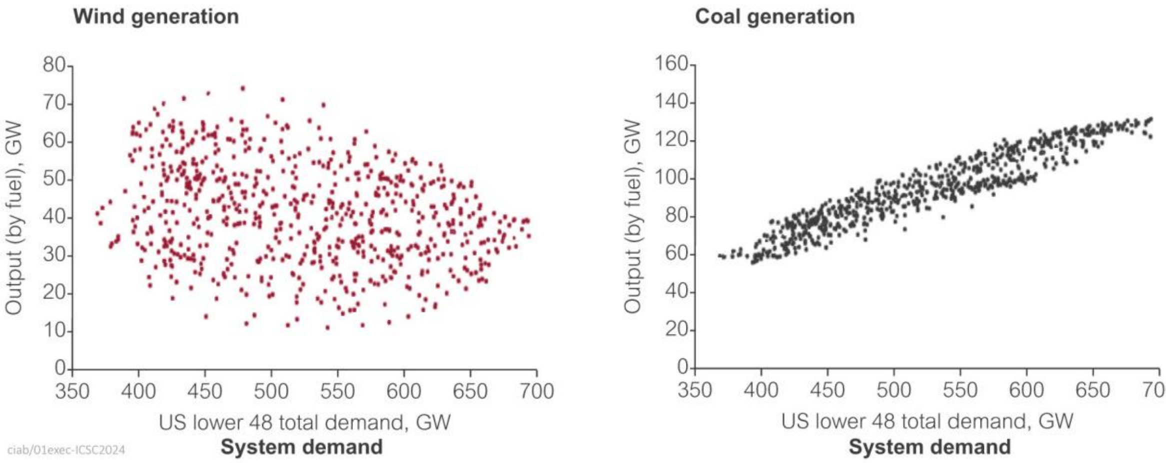

Figure 1 Correlation of output with demand for generation sources, June-July 2023, USA (Caravaggio, 2023)

Figure 1 illustrates the fundamental difference of VRE compared to other forms of generation in terms of delivering power on demand. There is little correlation between power generation and demand in the wind power example, and a strong one for dispatchable power.

It is therefore important to understand the supply-related risks. Many risk drivers are evolving simultaneously including the issues related to ageing infrastructure and increasing power demand due to the increased drive for electrification. Some regions have simultaneous demand increases related to economic development or population growth. Many areas are likely to see power demand double over the next 20 years.

There are issues due to grid congestion, and reinforcement requirements to handle the higher loading. Extreme weather events are more frequent and severe; increasing dependence on grids increases the risk of terror and cyber-attack. There are additional risks associated with change, affordability, speed of deployment, supply chains and materials availability as well as planning, policies and market reforms, altering how systems are operated, governed and rewarded. There is potential risk from an over-reliance on VRE in maintaining a stable, dependable, and affordable system, as efforts to decarbonise are accelerated.

> 'THERE IS A LOOMING RELIABILITY CRISIS IN OUR ELECTRICITY MARKETS' (COMMISSIONER JAMES DANLY, US FEDERAL ENERGY REGULATORY COMMISSION)

This statement, although referring to the US situation, reflects the broader findings of this CIAB study, the objective of which is not to conduct new research, but to assess and consolidate relevant related issues based on a review of existing materials and evidence in the public domain. The aim is to produce a report offering context and overview to maintaining grid and associated system security and reliability in the energy transition. This includes assessment and understanding of the implications of decisions being made concerning energy supply with respect to system stability, reliability, security, cost, and deliverability at a whole system level. Given the implications of decisions being taken, it is essential associated decision making is on a best-informed objective basis. This report supports a holistic approach to help ensure the road to net-zero is a smooth one.

> "YOU FORGOT TO BUILD THE ROAD" – IT'S TIME TO 'RING THE ALARM BELLS' ON ELECTRICITY GRID EXPANSION AND MODERNISATION AROUND THE WORLD, OR RISK PUTTING THE BRAKES ON THE TRANSITION
> (DR FATIH BIROL, IEA, JULY 2023)

MANAGING THE IMPACT OF VRE ON THE ELECTRICITY SUPPLY NETWORK

VRE integration requires grid adaptation. Many grid systems have some VRE capacity but also rely on legacy dispatchable power assets and interconnection to maintain security and reliability of supply. In addition, integration of VRE requires energy storage, curtailment, re-dispatch, grid modification, grid forming inverters and synchronous compensation, consumer flexibility, wholesale price volatility and market reform.

When only 25% of peak capacity is installed as VRE, issues become apparent:

- how to accommodate intermittent and variable output;
- reduced electrical inertia to ride through fault conditions;
- output is weather and time dependent, and non-dispatchable, therefore requiring backup generation availability;
- reduced capability to move bulk power from where it is produced to where it is needed;
- difficulty adding capacity rapidly due to small individual unit or plant sizes; and
- market volatility caused by over-supply and deficits, which may be good for energy traders, but not for system reliability management.

Therefore, there is a need for potentially expensive system-wide mitigations to integrate the higher VRE share being demanded.

BALANCING THE GRID AND WHERE WILL SYSTEM FLEXIBILITY COME FROM?

VRE is largely enabled by taking advantage of the flexibility of pre-existing systems but here there is a paradox. As system flexibility needs increase, flexible power assets that have enabled VRE are being decommissioned. If this continues, there may no longer be adequate flexible dispatchable capacity. Capacity derating factors associated with VRE, confirm VRE is not dependable in times of system stress and so other means are needed to provide flexibility.

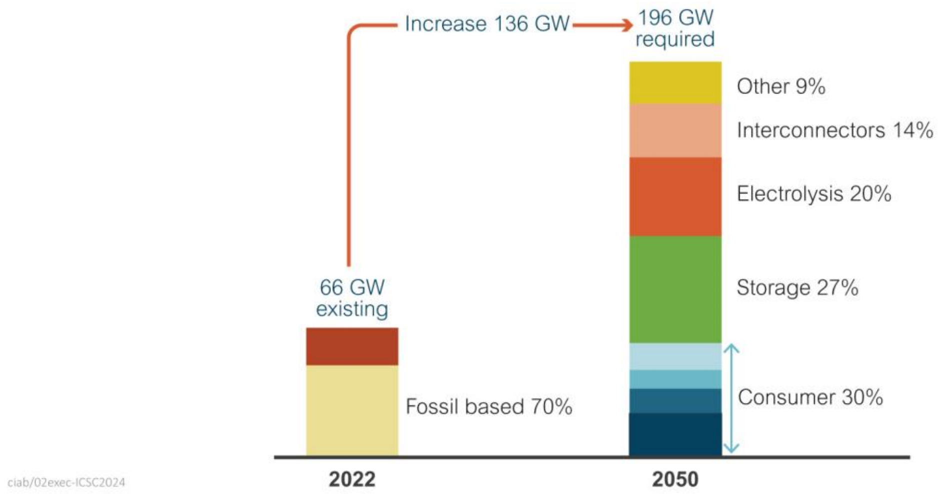

Figure 2 Total installed electricity system flexibility by 2050, UK (GW) (National Grid ESO, 2023)

Figure 2 illustrates a 2050 scenario with huge increase in flexibility demand evident but also an almost complete elimination of existing flexibility capacity. Yet it is *not* proven that reliance on consumer demand management, storage and interconnectors will be adequate, dependable, or cost-effective to satisfy needs at national scale in the future.

> 'SYSTEM FLEXIBILITY IS THE CORNERSTONE OF ELECTRICITY SECURITY. CHANGING DEMAND PATTERNS AND RISING SOLAR PV AND WIND SHARES DOUBLE FLEXIBILITY NEEDS IN THE IEA ANNOUNCED PLEDGES SCENARIO BY 2030 AND INCREASE THEM ALMOST FOURFOLD BY 2050'
> (IEA, OUTLOOK FOR ELECTRICITY, 2022)

Recent statements from the IEA reinforce that electricity security requires 'flexibility', which might also be written as 'dispatchability'.

IS SURPLUS VRE CAPACITY THE ANSWER?

Building excess VRE capacity is an option, but may not be a solution in still, dark winter periods for example. Building more interconnectors to share surplus power may not be sufficient, as similar weather patterns can be continent-wide. The cost of overbuilding is high and materials and resource intensive; also, the more VRE, the lower the load factor under average conditions.

Alternatives include shifting demand or introducing new industries which can absorb the surplus power, such as production of electrolytic hydrogen. However, the generation production costs would still need to be covered by energy sales and new industries would need to be viable businesses even accounting for the variability of the renewable energy surplus.

WHAT ARE THE CLEAN DISPATCHABLE POWER OPTIONS?

There is a range of clean dispatchable power options available, often complementary in nature. A resilient system is typically one with a broad technology portfolio able to adapt to a variety of different circumstances. A portfolio approach is likely to be better positioned to deliver decarbonisation needs.

Figure 3 illustrates the effect on relative system decarbonisation cost of excluding options from the portfolio, with particular emphasis on the impacts of removing carbon capture and storage (CCS) as an option. System decarbonisation is far more costly when CCS is not an option, *especially* if national solutions are based on VRE and storage only.

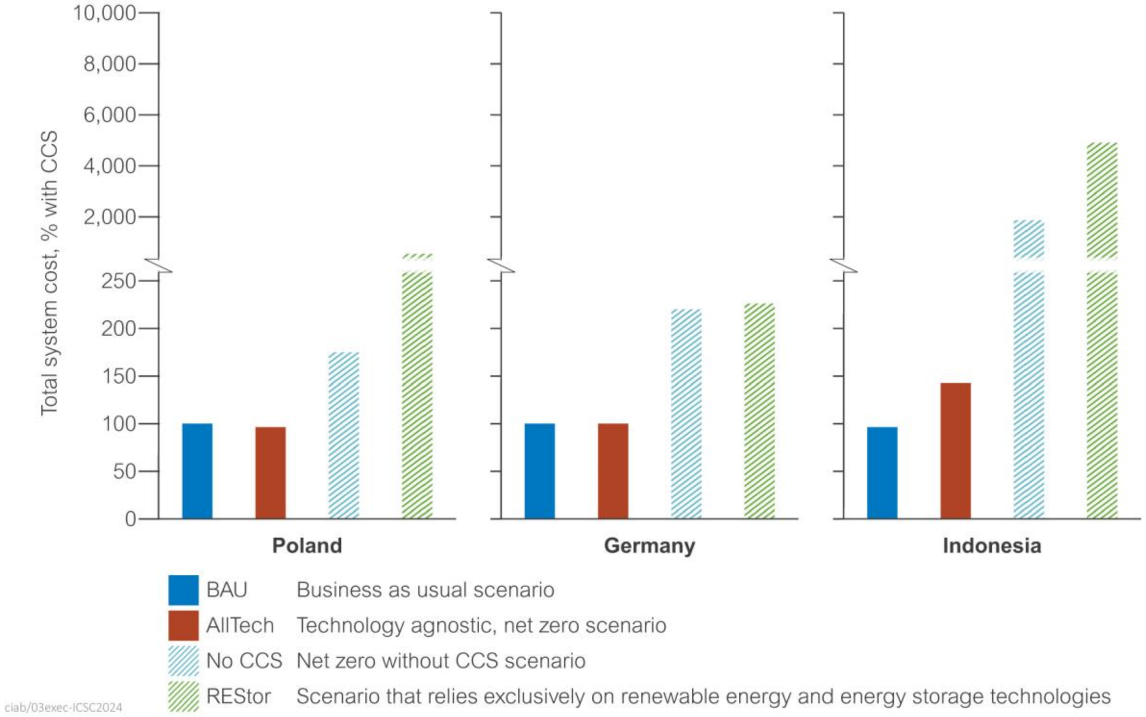

Figure 3 Total system net zero cost comparison by technology mix (Pratama and Mac Dowell, 2022)

It is therefore critical for a reliable, low cost, power system, that viable technologies are not excluded. Action is clearly needed on decarbonisation but on a cost effective, secure and deployable basis.

Dispatchable technologies are required not only for smoothing out variations in VRE output but also, critically, to bridge extreme system events, especially those of significant duration.

> A MORE HOLISTIC AND TECHNOLOGY AGNOSTIC APPROACH CAN DELIVER A FASTER, MORE ACHIEVABLE, AND LOWER COST TRANSITION TO NET ZERO

CAPACITY FACTORS UNDERPIN FINANCIAL VIABILITY

Having a diverse energy mix is one thing; how often, and at what capacity it is operated relative to the optimal economic case is another and is critical to the affordability and business model of any future option. The selection of future modification and retrofit options is dependent on assumed capacity factors.

Figure 4 illustrates how choices might be affected in the case of CCS. There is an inversion of the most economic options depending on the assumed capacity factor of the plant; CCS is significantly more economic unless capacity factors are very low. Low-capacity factors, and high flexibility requirements, not only impact operational costs, but also, the viability of providing critical dispatchable plant in the future.

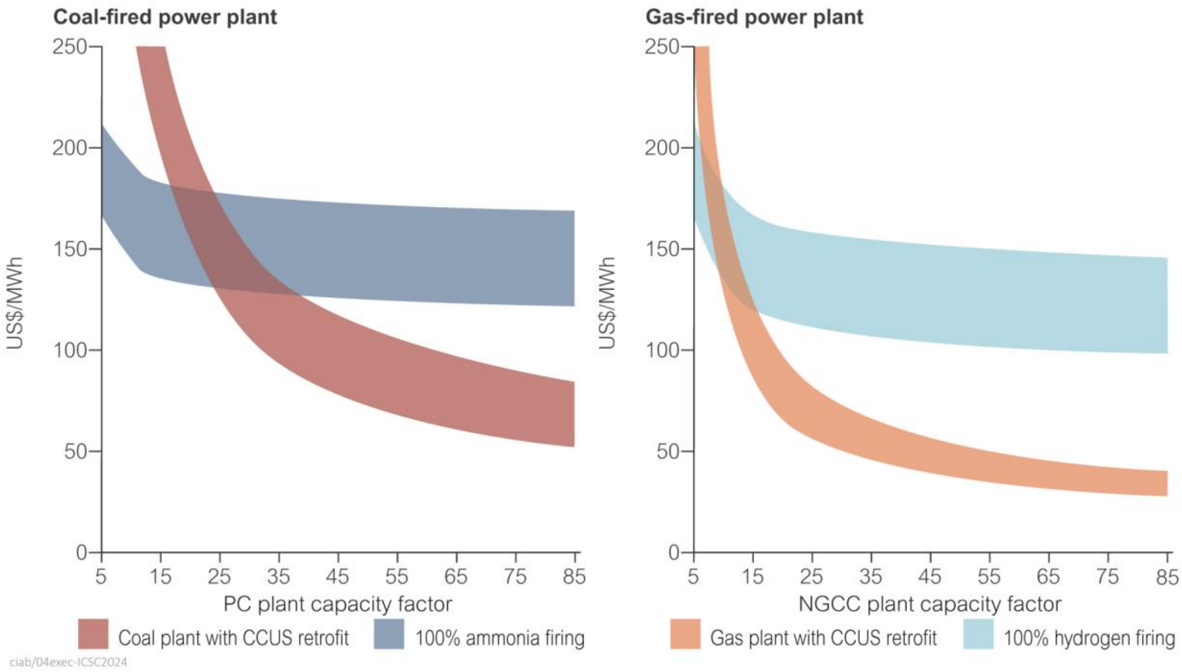

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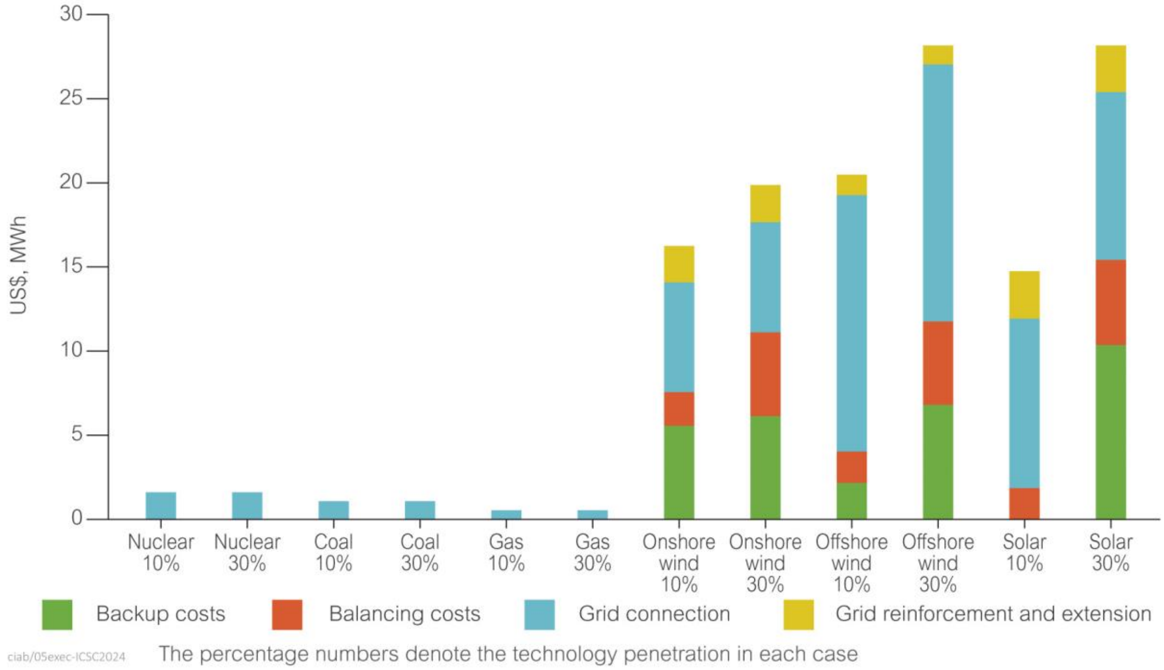
Figure 4 **Additional costs of ammonia, hydrogen abatement of existing fossil plants (IEA, 2023h)**

UNDERSTANDING AND CALCULATING TOTAL SYSTEM COST

Calculating cost is complex and cannot be simplified and generalised. Costs differ in time and place for the same thing, and are continually distorted by taxes, incentives, project and market conditions. Only cost ranges exist and can overlap widely for a range of technology options meaning that any of the overlapping options could be the least cost in particular circumstances.



ciab/05exec-ICSC2024 The percentage numbers denote the technology penetration in each case

Figure 5 **Grid-level system integration costs of technologies in the USA (Watt-Logic, 2023)**

Standard levelised cost of electricity (LCOE) can only be used for comparison where the impact of options considered are identical outside the boundary of the cost calculation. However, system wide impacts are generally not included in plant LCOE calculations and so LCOE cannot be used directly to compare the economics of dispatchable and non-dispatchable power sources. For VRE technologies this means firming, networks, storage and system stability costs fundamentally change the messages portrayed by most LCOE figures (*see* Figure 5). To calculate the full cost impact, many factors need to be considered to offer a valid comparison, including permitting, connection, extension, reinforcement, interconnection, synchronous compensators, grid forming inverters, energy storage, curtailment, redispatch, voltage regulation, backup dispatchable generation, taxes, incentives, subsidies, levies, rebates, mandates, market price volatility, consumer flexibility, and regulatory changes. Additionally, the 'cost' a consumer sees is not the project or plant cost, but the total system cost impact, reflected in consumer prices. This price includes a large share of costs for transmission and distribution networks but also government costs, taxes, levies and incentives. So, assuming a correlation between LCOE and consumer price is not correct.

Flaws in LCOE calculation are widely known, as illustrated by the quote from EPRI, and have been the subject of many technical papers, yet it continues to be used and quoted on a regular basis.

> 'LCOE IS BARELY MORE THAN A BACK OF THE ENVELOPE CALCULATION. THEY DO NOT EVALUATE HOW THE MARKET VALUE AND ANCILLARY SYSTEM COSTS OF TECHNOLOGIES VARY AS THE STATE OF THE SYSTEM EVOLVES OVER THEIR FUTURES'
> (EPRI, 2020)

MODELLING LIMITATIONS

Models offer insights, stimulate useful discussion and problem solving. However, they can provide a false sense of security. Outputs may appear to be factual with precise numbers, trends, and graphics, yet they vary in their ability to represent real world conditions, costs, and deployment. Many models are flawed due to their narrow scope, assumptions, or over-simplifications, or a failure to consider related issues and systems like markets, supply chains, regulation and real-world business models. Modelling gets harder as systems become more complex and interconnected with more stakeholders and combinations of options.

Multiple models are needed with varied scopes and focus, addressing both the macro issues and the granular detail, down to modelling the actual physical systems, users and timelines. They should all be run against a wide range of scenarios to develop a robust picture of possibilities and constraints.

In terms of failure prevention, the most important things to model are extreme events – rare circumstances which place highest demand on the system and test resilience. The MEGS model, developed for use on the Australian National Electricity Market (NEM), is a good example. It considers not only capacity, carbon and cost, but also grid system inertia, stability and firming. Models of this type show a characteristic trend of increasing cost with decarbonisation, with a clear exponential trend for deeper decarbonisation levels, as illustrated in Figure 6.

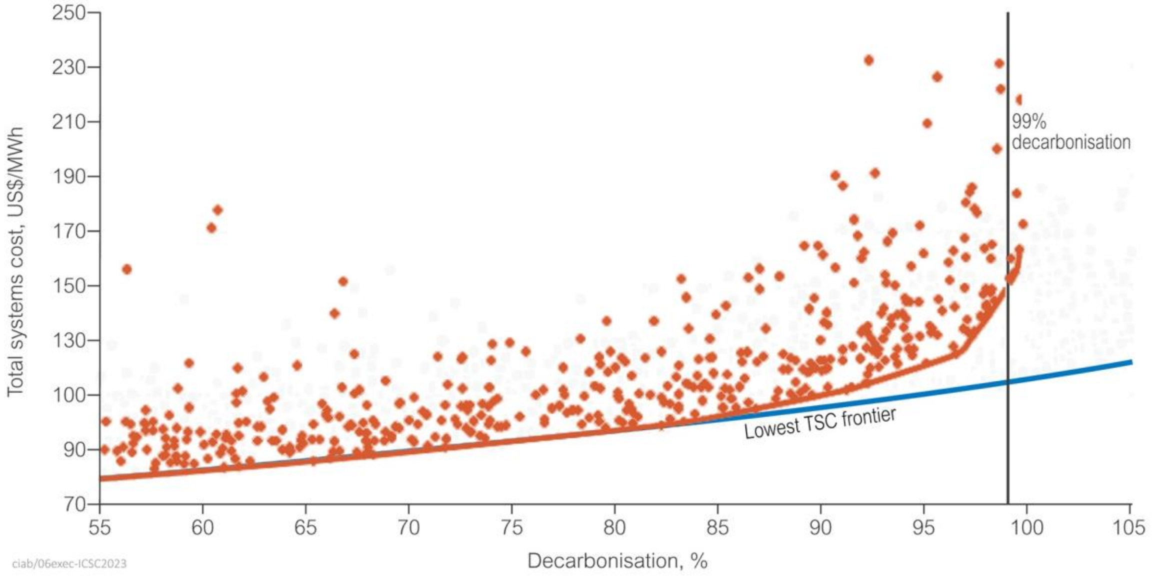


Figure 6 3000 Scenarios of the MEGS model for the Australian NEM (Boston and Bongers, 2021)

TIMING AND DECISION MAKING

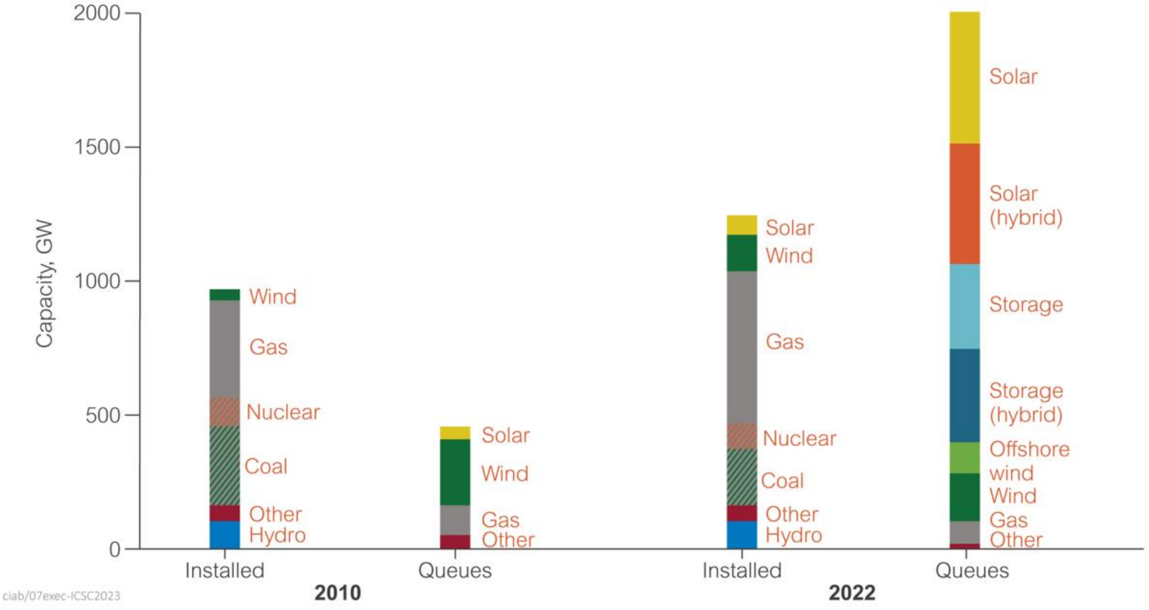


Figure 7 Comparison of US installed and queued capacity, 2010-2022 (Rand and others, 2023)

Technology installation takes time. High-capacity options typically take 6–12 years to reach commercial operation, and grid developments can take 5–15 years to implement. Figure 7 shows US installed capacity and the queue for approval of new capacity projects for 2010 and 2022; capacity awaiting permitting in 2022 was almost twice the total currently installed generation fleet. Globally, over 3000 GW of renewable capacity awaited permitting in 2023. Thus, for any technology option, decisions need to be made sufficiently in advance (15 years or more) to enable planning and deployment before that option becomes critical to the system.

MATERIALS AVAILABILITY AND INTENSITY TO DELIVER ON VRE DEMAND

Materials requirements, on an electricity output basis, are much higher for VRE technologies than large dispatchable assets. Table 1 illustrates major construction material requirements for a range of generation technologies and shows intensity is around 32 times greater for VRE technology.

TABLE 1A RELATIVE CONSTRUCTION MATERIAL BY TECHNOLOGY, T/TWH (WORLD NUCLEAR ASSOCIATION, 2021)

	Coal	Gas CC	Nuclear	Hydro	Wind	Solar PV
Concrete and cement	870	400	760	14,000	8,000	4,050
Iron/steel	310	170	165	67	1,920	7,900
Copper	1	0	3	1	23	850
Aluminium	3	1	0	0	35	680
Glass	0	0	0	0	92	2,700
Silicon	0	0	0	0	0	57
Total metals	314	171	168	67	**1978**	**9430**

TABLE 1B RELATIVE CONSUMPTION OF CRITICAL MINERALS BY TECHNOLOGY (WORLD NUCLEAR ASSOCIATION, 2021)

	Plant, t/MW	Indicative, CF, %	TWh/y	Operational lifetime, y	Lifetime, TWh	Plant, t/TWh
Coal	2.5	85	7.5	50	375	7
Nuclear	5.3	85	7.5	60	450	12
Gas	1.2	60	5.2	30	156	8
Solar	6.8	25	2.2	25	55	**124**
Onshore wind	10.1	35	3.1	25	78	**130**
Offshore wind	15.5	35	3.1	25	78	**200**

CC – combined cycle; CF – capacity factor

A similar calculation is provided in the lower chart for critical minerals where an intensity of 17 times higher is indicated. Critical minerals are becoming a contested resource with demand set to outstrip supply on the current net zero pathway. The numbers in Table 1 relate only to direct material requirements and exclude materials associated with other system requirements like grid expansion, storage, and backup power generation. The IEA's 2023 grid report highlighted that 80 million km of grid network needs to be built by 2040, requiring over double the annual copper and aluminium supply relative to 2021 to meet a net zero scenario.

ELECTRICITY SUPPLY MARKET CONCERNS

Regulators and operators are raising concerns about system reliability. In the Australian NEM, system operator AEMO has forecast that system reliability standards could be breached in some areas by 2025 on the current path.

VRE heavy systems around the world rely on gas and coal power plants and interconnectors for continuity of supply. Extreme flexibility demands are being made on these plants, to accommodate the high volatility of VRE output, with associated consequences on integrity, efficiency and operating costs. There are also reports of VRE costs increasing, and of new VRE projects no longer being economically viable, with auctions under-subscribed and suppliers requiring state aid. Areas with high VRE share also seem to be the ones with the highest, rather than the lowest, consumer power prices.

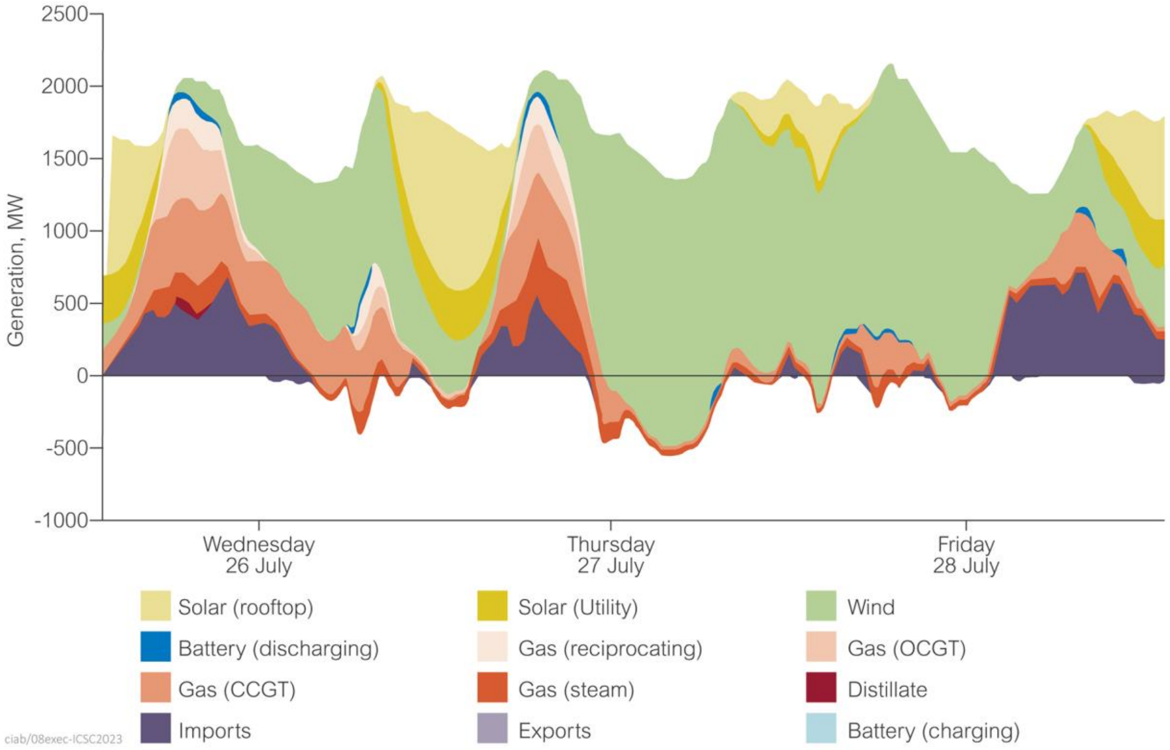


Figure 8 The grid in South Australia, July 2023 (Hunt, 2023)

Figure 8 illustrates that late on 26 July in South Australia there was more wind energy than total system demand. However only 24 hours earlier, wind and solar output was near zero and system load was carried almost entirely by natural gas and interconnectors. This illustrates not only the real-world issue of the surplus-deficit cycling of VRE, but also the reliance of system stability on dispatchable power, whether from the same grid, or adjacent grids via interconnectors.

It is precisely these alternate surplus and deficit cycles associated with VRE that future markets and systems must be designed to accommodate seamlessly and at national scale.

> VRE IS NOT A COMPLETE SOLUTION ON ITS OWN, BUT ONLY PART OF ONE. DISPATCHABLE CAPACITY REMAINS A NECESSITY TO ENABLE VRE TO FUNCTION

KEY MESSAGES

- Grids are vast and complex; modern society relies on them.
- They must be dependable under all conditions.
- Grid system related risks are diverse, evolving and increasing.
- VRE requires additional measures, beyond minor capacity share, to ensure stable dependable and cost-effective systems can be deployed.

- VRE technologies are resource intensive compared with other large capacity low-carbon dispatchable power options.
- Currently, cost analysis is not sufficiently transparent to identify the total cost impacts of energy and technology options.
- A balanced and technology agnostic approach must be adopted to ensure timely, lowest cost decarbonisation.
- Storage, interconnection and demand management alone are not sufficient to guarantee system dependability under all conditions.
- Dispatchable power remains a necessity and is critical to ensure system security and reliability.
- Different starting points, drivers, and constraints, lead to different paths and speed of change by geographic region.
- Abated fossil fuel has the potential to reduce the cost of, and to accelerate, grid decarbonisation at global scale and help address decarbonisation challenges in regions still reliant on fossil fuels.

As yet, no major grid system has demonstrated a reliable, affordable transition pathway to net zero.

KEY RECOMMENDATIONS

- Modelling needs to focus more on resilience to extreme events than business as usual.
- Cost comparisons between options should only be made on real-world cost bases including the impacts on the wider energy system. Simple plant LCOE analysis should not be used and should be avoided wherever possible.
- Sufficient dispatchable generation remains essential until any proposed alternatives are demonstrated, deployed and proven.
- Policies and finance mechanisms need to be fit for purpose and explicit about differentiating between abated and unabated fossil fuel to transition optionality.

> ‘CURRENT TRENDS INDICATE THE POTENTIAL FOR MORE FREQUENT AND MORE SERIOUS LONG DURATION RELIABILITY DISRUPTIONS, INCLUDING THE POSSIBILITY OF NATIONAL CONSEQUENCE EVENTS’
> (JAMES B ROBB CEO, NERC)

Electricity grids must provide dependable, affordable, stable and secure power for our societies and economies, and this *must* continue to be our priority throughout the low carbon energy transition.

The International Centre for Sustainable Carbon (ICSC) was commissioned to produce this study by the International Energy Agency’s (IEA) Coal Industry Advisory Board. The ICSC is organised under the auspices of the IEA but is functionally and legally autonomous. Views, findings and publications of the International Centre for Sustainable Carbon do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

Each executive summary is based on a detailed study which is available separately from: www.sustainable-carbon.org. This is a summary of the report: Maintaining a stable electricity grid in the energy transition by Mike Garwood, ICSC/CIAB, 240 pp, January 2024.