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Beyond Baseload Power

Toward a New Paradigm of Power System Operation

Acknowledgements

Lead Author:

Toby D. Couture (E3 Analytics)

Co-Authors:

Owen Zinaman (Source Clean Energy)

Joseph Thomas (E3 Analytics)

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Baseload power has become a flashpoint in the global debate on the future of the power system. Proponents argue that baseload sources of power are necessary to meet electricity demand 24/7.

And yet, a series of cascading economic and technological changes is putting strain on this century-old system. In the process, **a new paradigm of power system operation is emerging.**

1

Baseload Power: The Origins

First recorded usage in English: “The company also owns some water power property which can in the future be economically developed, and this, supplemented by its steam apparatus, will furnish the company with ideal power conditions both for base load and peak.” Stone and Webster, 1907, p. 311[1]

The origins of the term “baseload” power

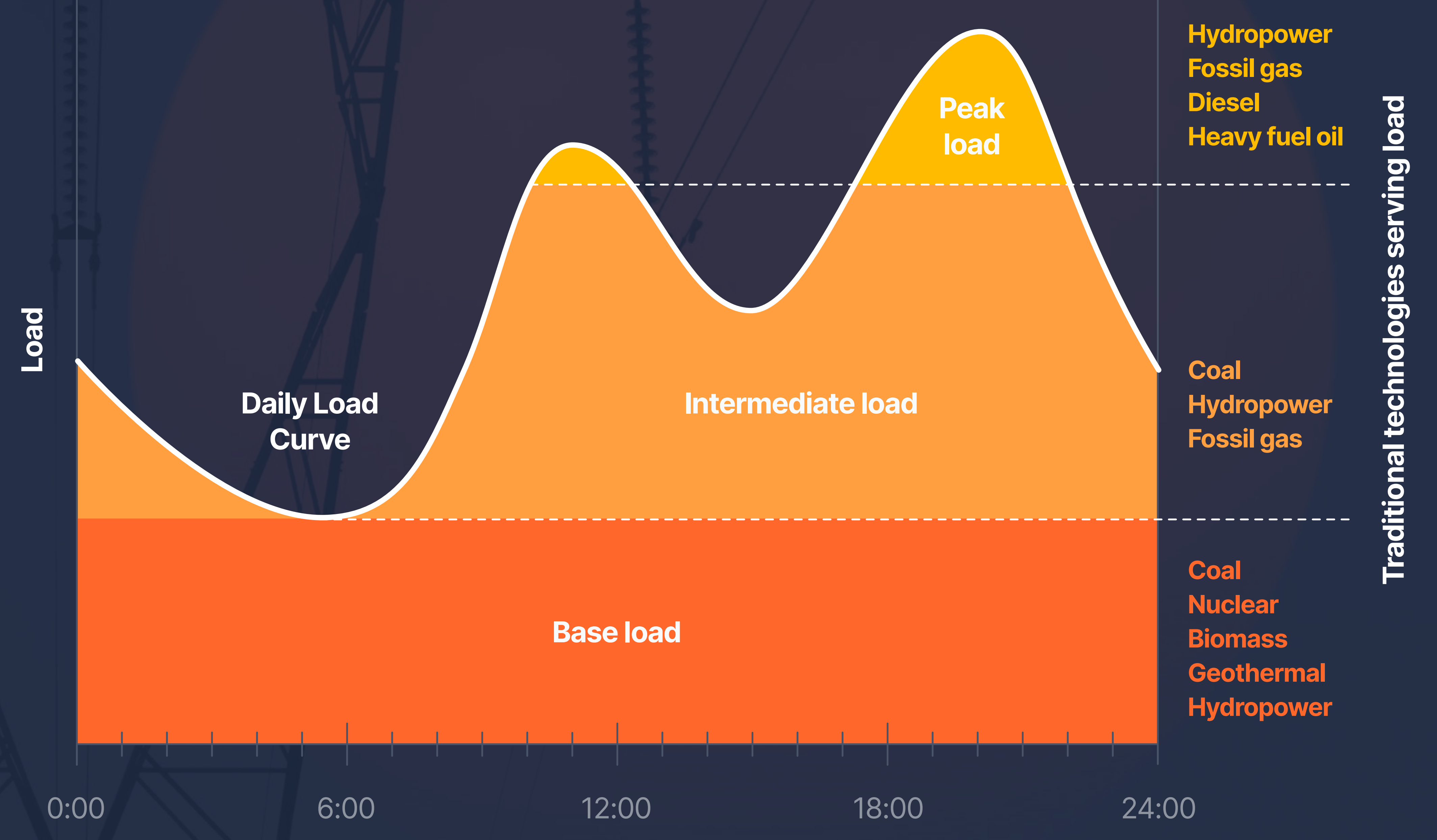
- The first documented use of the term “base load” was in 1907 in the utility industry journal “Stone & Webster”.
- The term was initially used to refer not to the type of generator, but rather to the nature of the load (i.e. of the electricity demand).
- It referred specifically to the stable “band” of electricity demand that industrial customers often required to sustain production.

Baseload referred to the stable "band" of electricity demand

- This stable electricity demand had several upsides: by providing a steady buyer, it helped ensure stable revenues for early investors. Also, steady demand helped plan and dimension power plants accordingly.
- Throughout the first decades of the 20th Century, the bulk of "baseload" power supply was provided either from hydropower, coal, or from steam engines burning liquid fuels.
- Today, while only roughly 40% of the world's power generation capacity can be considered "baseload", it forms the backbone of many power systems.

Typical electricity demand profile

(Illustrative)



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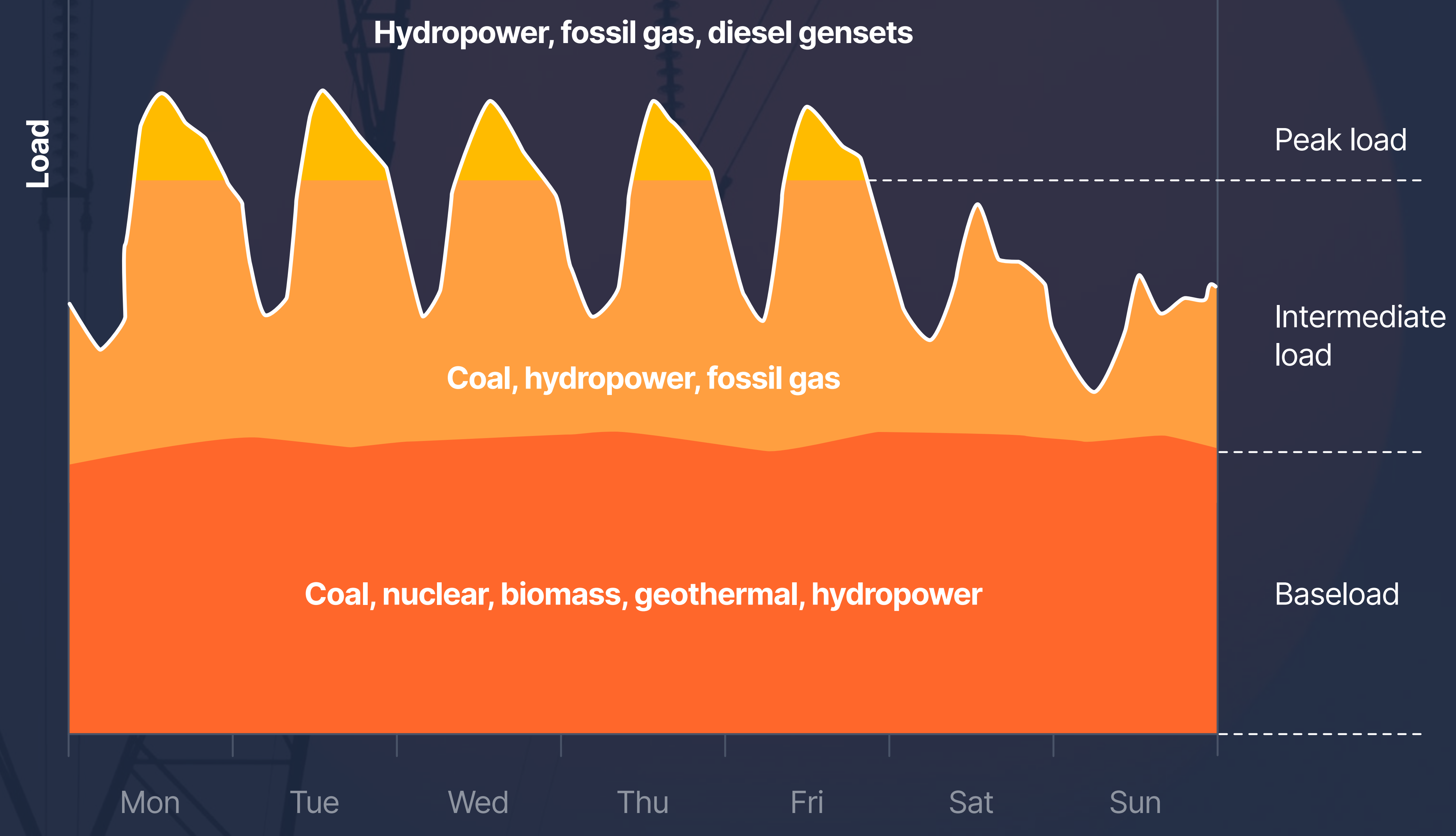
How baseload power systems work

- In much of the world, **“baseload”** power plants* are designed to run as close to their maximum output as possible** to achieve the lowest overall operating cost.[2]
- On top are added so-called **intermediate** or “mid-merit” power plants, which constantly vary their output to meet the fluctuating demand beyond that “base”.
- Finally, there are **peaking** power plants, which typically come online to meet the shorter “spikes” in electricity demand as they arise.
- Hydropower plants (especially those with a reservoir) are particularly valuable assets for many power systems in that they can provide all three.

* Strictly speaking, the term “baseload plant” is inaccurate, as coal and nuclear plants can in principle be ramped down when needed. However, both their operational and economic efficiency tend to suffer, wear-and-tear increases, and plant lifespan can be shortened.
** Consistent with their peak thermal or operational efficiency.

The use of conventional power plants to meet overall demand in a power system without renewable energy sources

Source: Grist (2012)[3]



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Baseload power systems also need flexibility

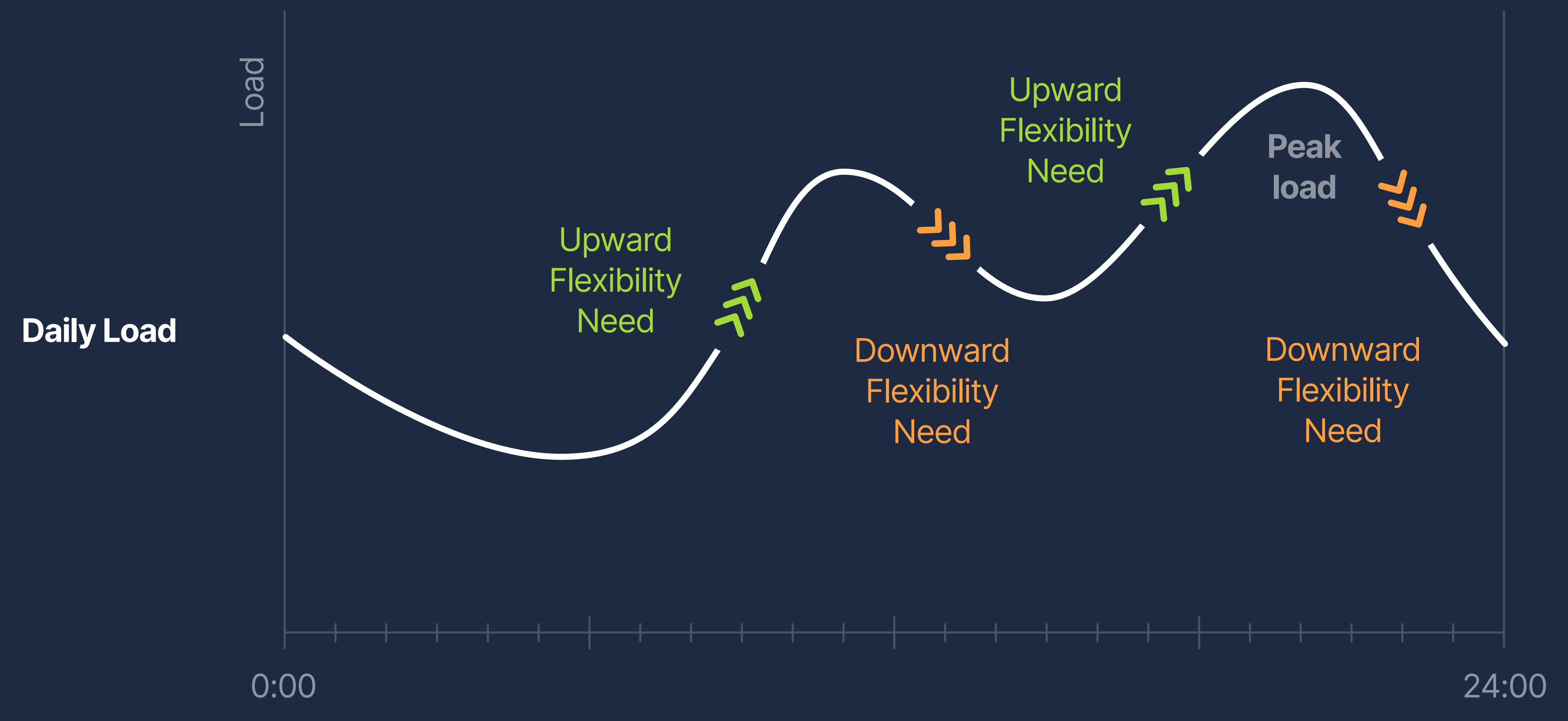
In a power system anchored to traditional baseload power plants, the flexibility in the system is provided by intermediate and peaking power plants.

This flexibility is vital for meeting the frequent fluctuations in electricity demand.

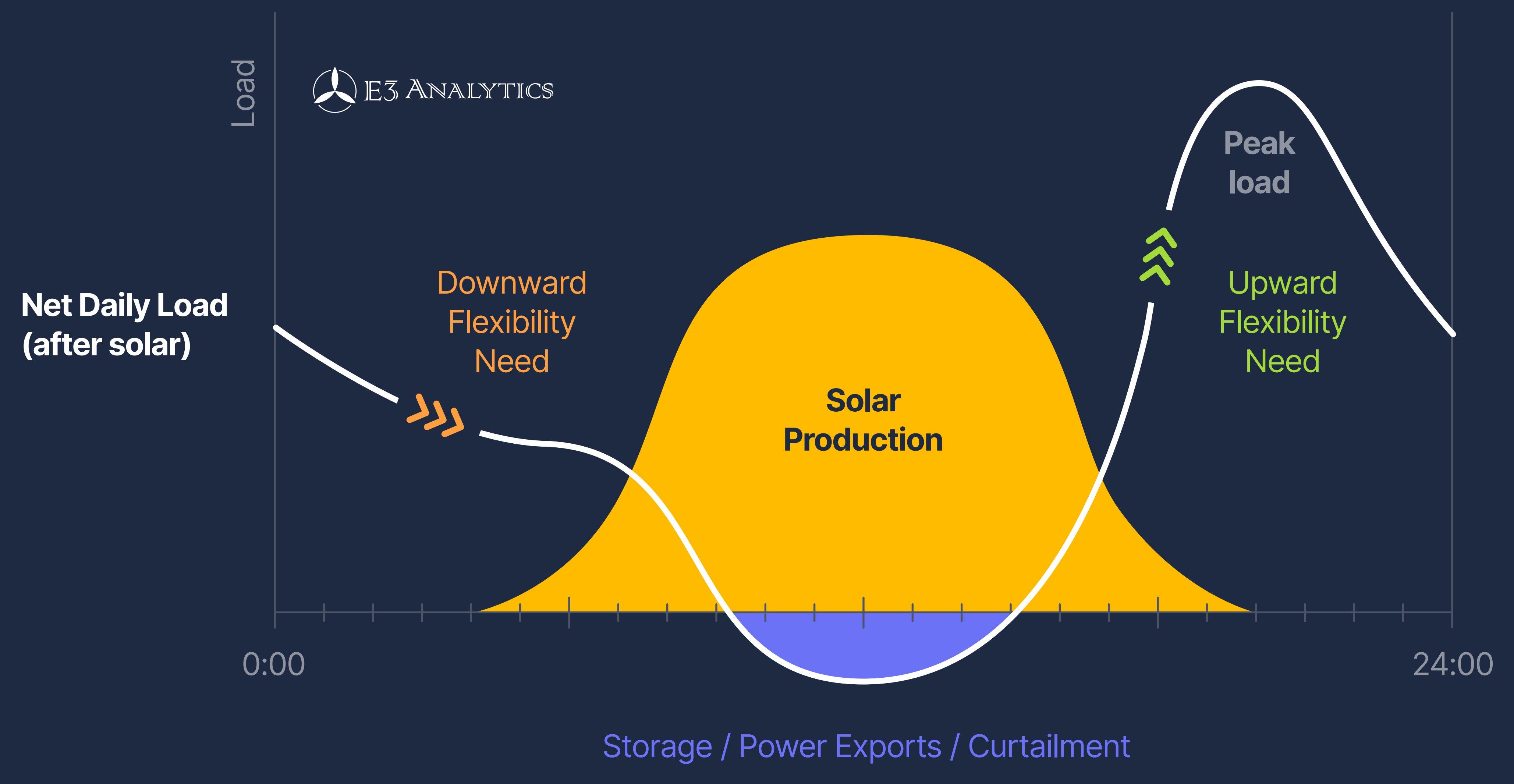
In a power system with variable renewables at its base, a high degree of flexibility is also required.

While the flexibility requirements are occasionally greater, such as when the sun sets, **the need for power system flexibility is common to both paradigms**.

Conventional baseload paradigm



Renewable paradigm



Baseload power plants provide more than just electricity

- Conventional baseload generation plants often provided a range of system services as well, such as **inertia**, **frequency control**, and **black start** capabilities.
- These grid-stabilizing services were long considered “part of the package”, a valuable upside of having generators with large rotating masses in the system.
- While these **ancillary services** can now be provided via inverters technologies using power electronics, many power system engineers still struggle to envision a power system operating reliably without these large rotating masses.

baseload

Grundlast

基荷电力

حمل الاساس

базова мощност

As electricity spread across
North America, Europe, Asia and beyond,
the term “baseload” persisted, and was adopted
in various forms in other countries
such as Germany, where it is referred to as
“Grundlast”, in Bulgaria (“базова мощност”),
in Arabic-speaking countries (حمل الاساس),
and in China (“基荷电力”).

2

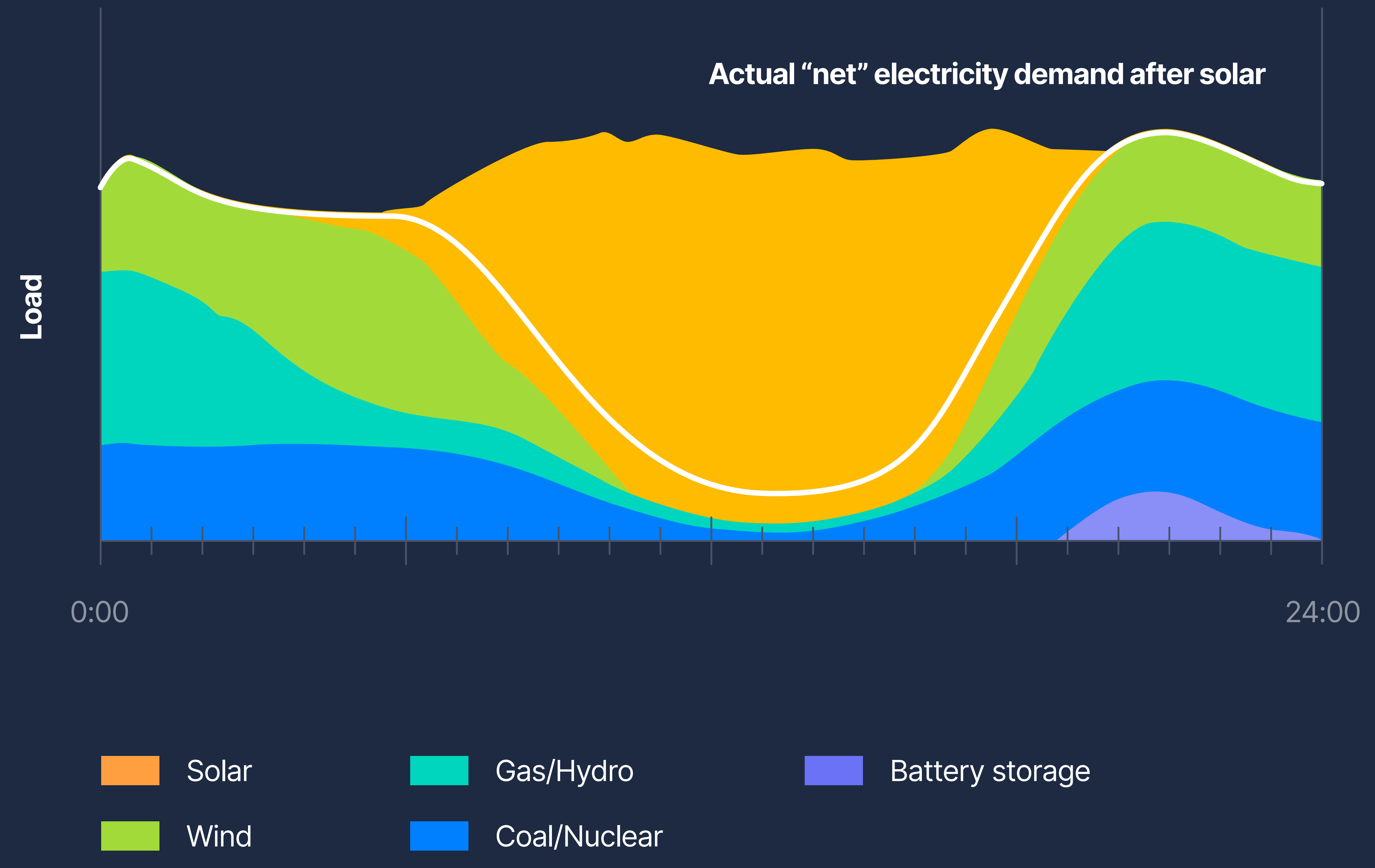
Understanding the Shift

The shift beyond baseload power is well underway

- Driven by near-zero marginal costs and record-breaking deployment in recent years, wind and solar are fundamentally reshaping power system operation.
- The reason is that **most power systems dispatch the lowest-cost resources first**.
- The result is that technologies like wind and solar are gradually eating into the "baseload" demand, and the plants that have historically been used to meet this demand are being asked to operate more flexibly.
- Put differently, they are being asked to operate **less**.

When an electricity system achieves a relatively high share of variable renewables like solar, there is less and less "room" left for inflexible baseload supply

Illustrative



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Different power systems can be thought of as being at different stages

- Base supply
- Intermediate supply
- Peak supply
- Dispatchable generation
- Variable renewable energy
- Demand shift
- Surplus (for storage/export)
- Imports / stored electricity
- Demand

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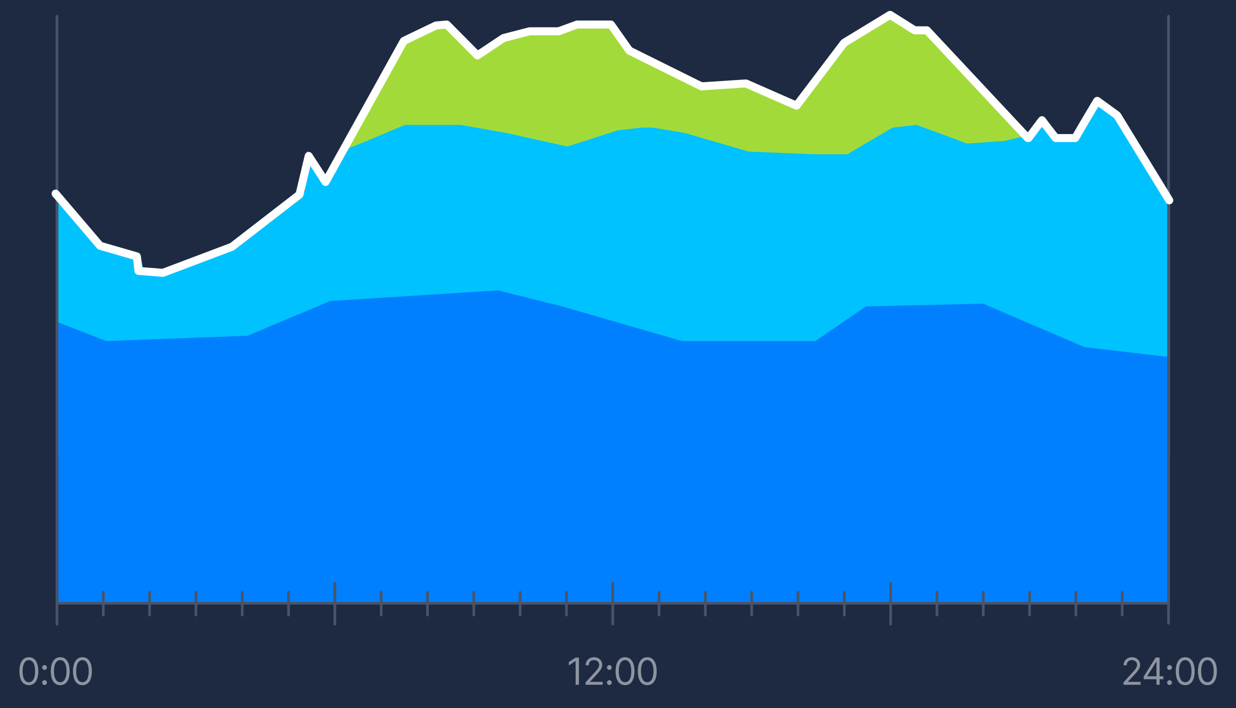
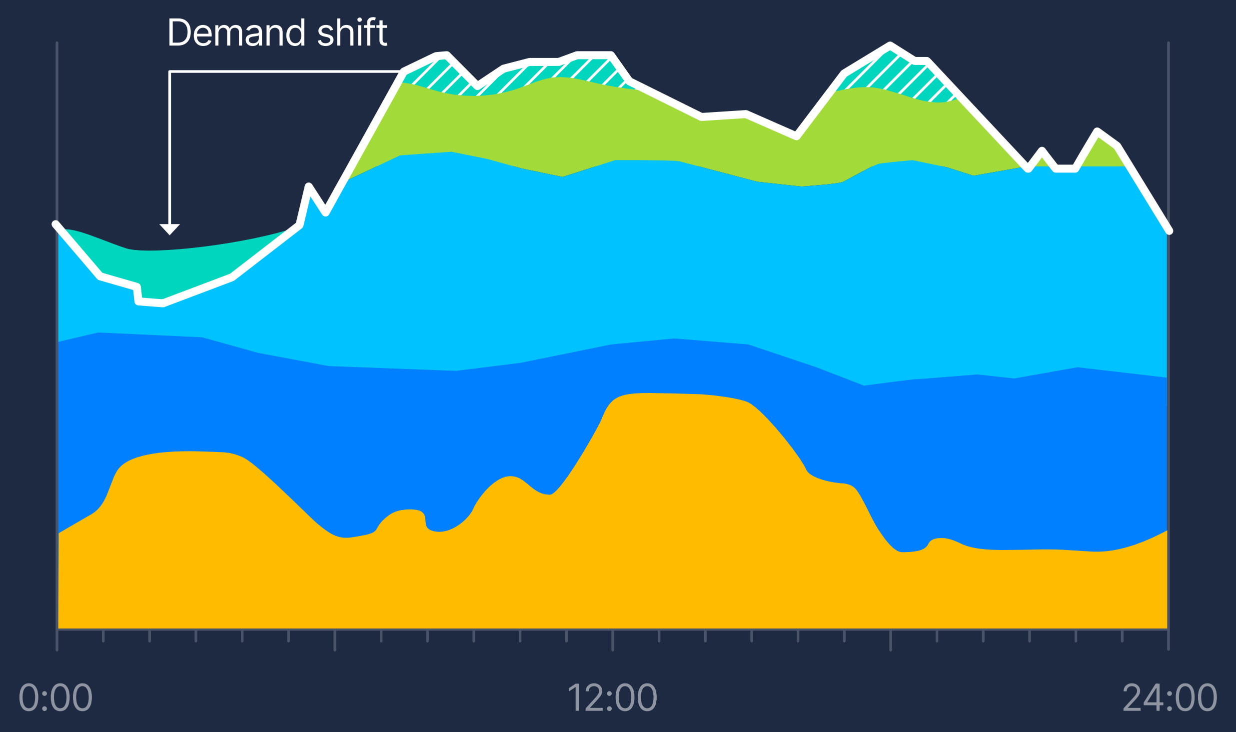


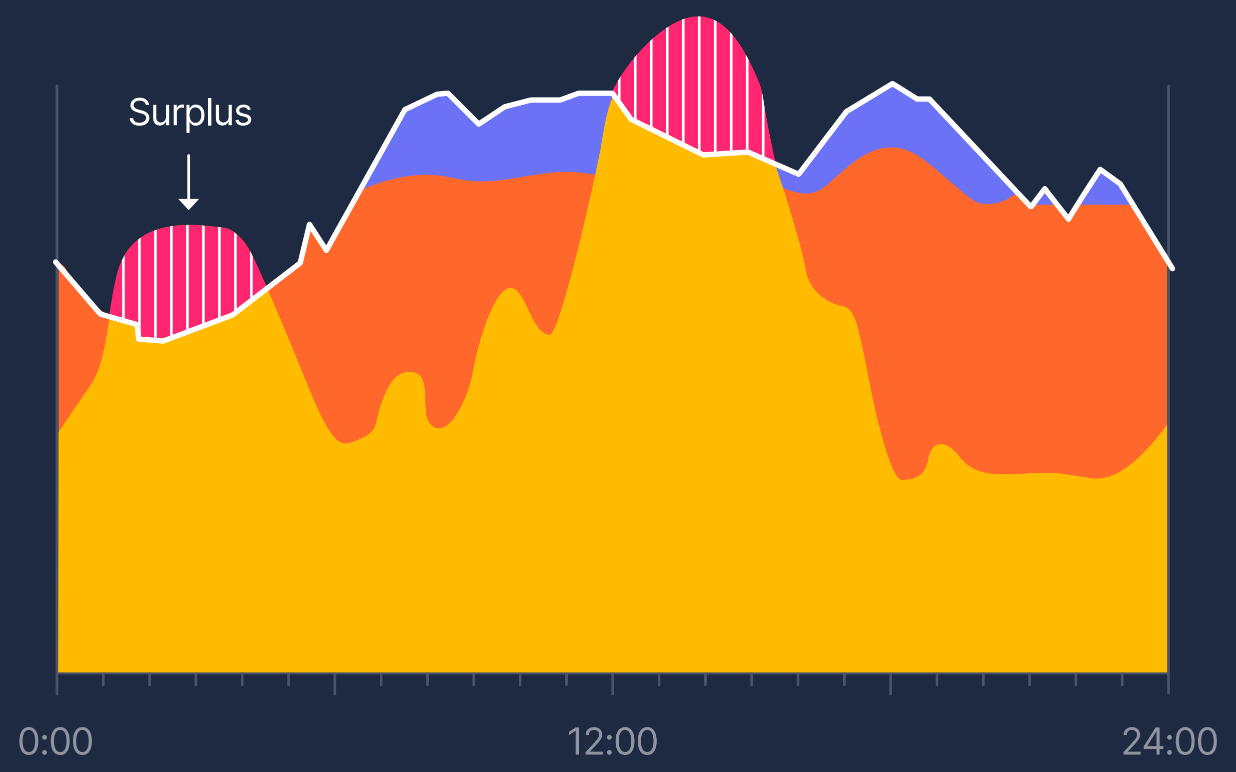
Stage 1: The Baseload Paradigm

Conventional baseload generation provides the bulk of the system’s electricity needs, with more expensive, flexible resources layered on top to help keep supply and demand in balance.



Stage 2: The Early Transition

Renewables start to displace more baseload generation, and even meet a large share of demand during certain days and weeks, but baseload generators remain the primary source of electricity.

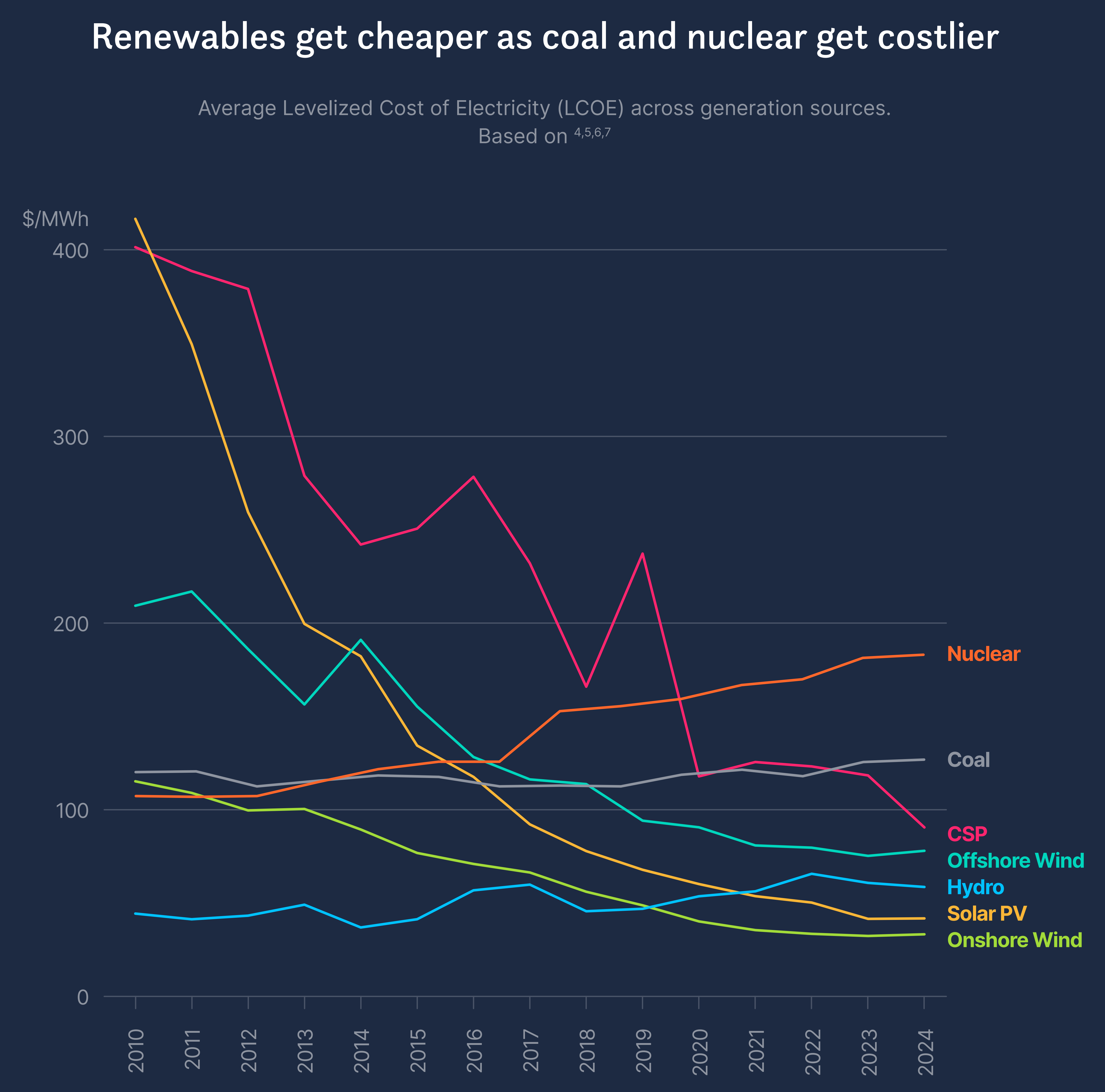


Stage 3: A New Paradigm

Low-cost renewables like solar and wind come to dominate daily, weekly, monthly and even annual electricity supply; they regularly supply more than 100% of a region or country’s power needs.

The shift away from "baseload" power plants is being driven mainly by economics

- For over a century, power systems were designed around "baseload" power provided by coal, nuclear, and/or hydropower power plants.
- In previous decades, it often made sense to design power systems around baseload, as such power generation sources were commonly the lowest cost.
- This is no longer the case, with new renewables undercutting traditional baseload generation sources on price in markets around the world.

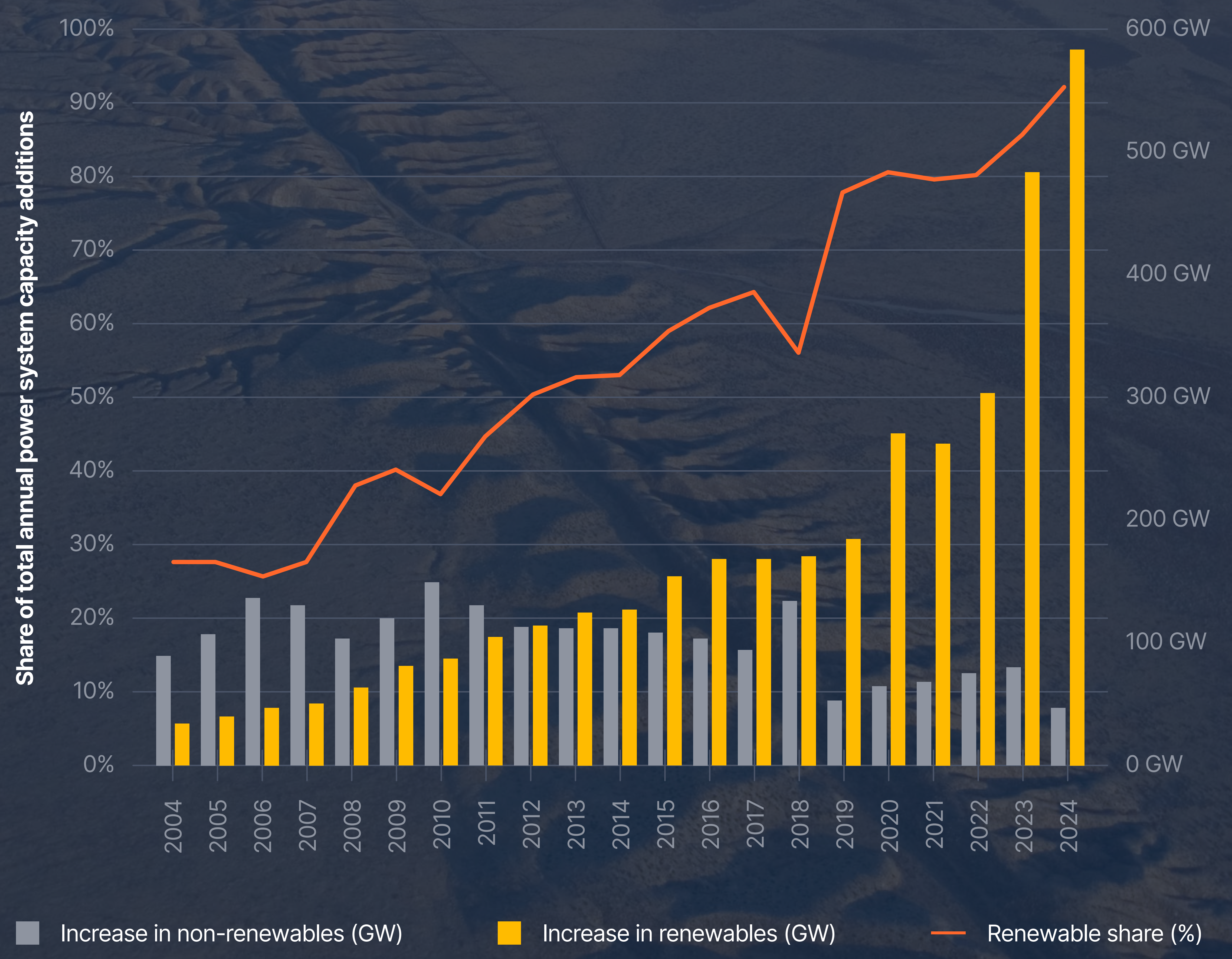


This represents a tectonic shift in the way power systems are planned and operated

- **New technologies like solar, wind, and storage are colliding with legacy power systems and the institutions built up around them.**
- Renewables now dominate new investments in power generation worldwide, with solar and wind alone now representing over 90% of global power system capacity additions.
- The main reason behind this surge in investment is that they are cheaper and faster to build.

Renewables now represent over 90% of new power generation capacity added each year worldwide

Source: CleanTechnica[8]

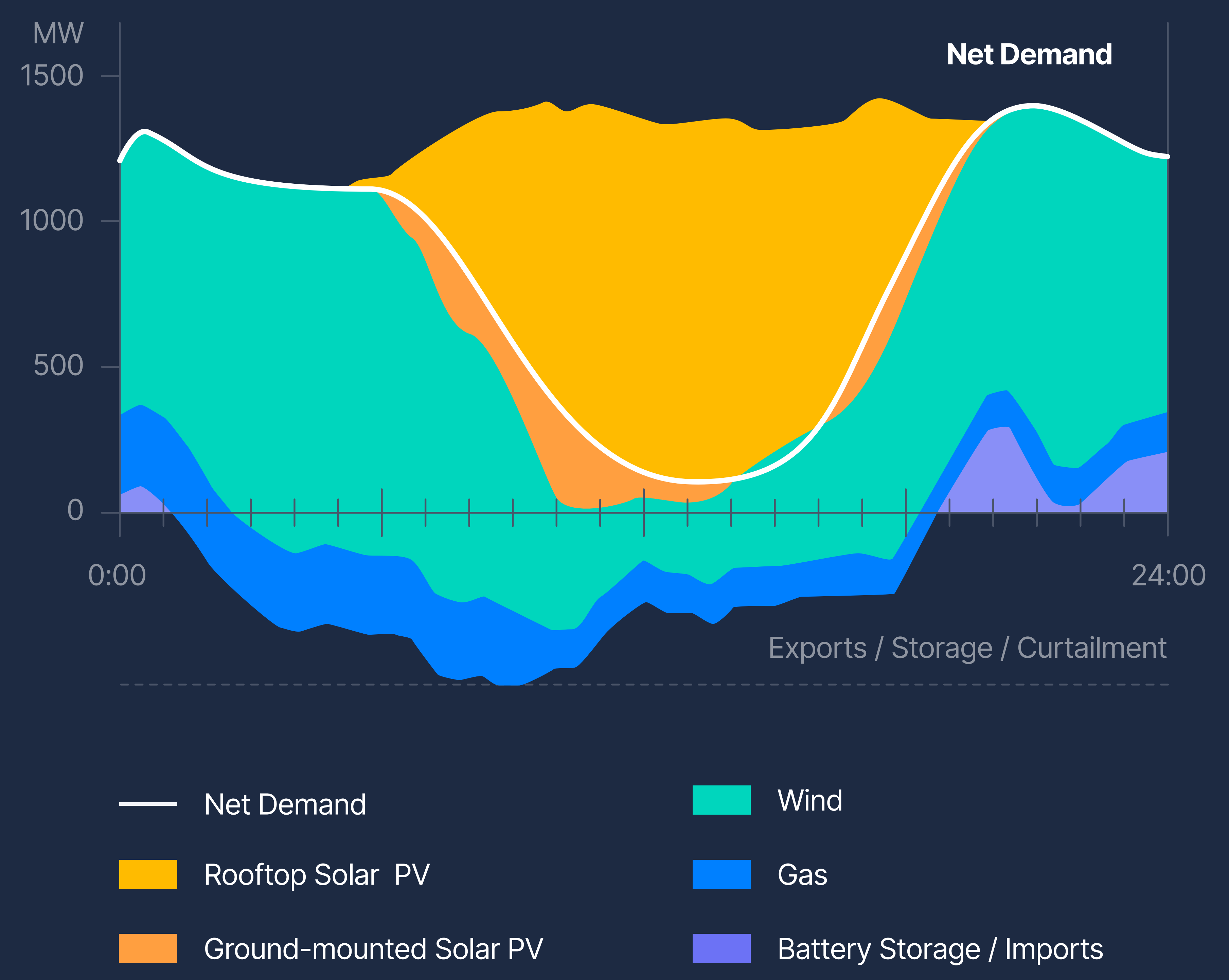


There is no clearer indication of this tectonic shift than the daily “baseload disappearing act” that occurs now nearly daily in parts of Australia

- With a surge of investment in rooftop solar from households and businesses, “net” electricity demand* in South Australia is now frequently negative.
- In other words, **rooftop solar alone now meets more than 100% of total, system-wide electricity demand**.
- Combined with wind power, there is less and less room in the system for inflexible baseload supply sources.

Demand and generation mix in South Australia

Generation type [MW] / Demand [MW], Sunday 21 November 2021
Source: Australia Energy Market Operator[9]



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* Net electricity demand = demand after rooftop solar has been injected into the system

Today’s power system was not designed or built to have variable, zero-marginal-cost power as its foundation

The result is three major forms of stress:

Economic Stress

- Lower operating hours for baseload plants means increasingly strained economic model for baseload plants and lower revenue for incumbent utilities who own baseload assets

Technical Stress

- Today’s grids were planned to get the bulk of the electricity from large, centralized power plants — not variable renewables.
- Lack of proactive planning leads to grid bottlenecks
- System operators were trained on synchronously connected, dispatchable generation: managing a grid based around solar and wind requires new tools (e.g. more sophisticated forecasting) and new skills (including new software).

Political Stress

- Traditional utilities often do not own the new VRE generation.
- Entrenched interests are losing power and often resist reform.

3

Economic Tensions

Low-cost renewables are putting the baseload model under strain

Renewables are now the cheapest source of electricity worldwide

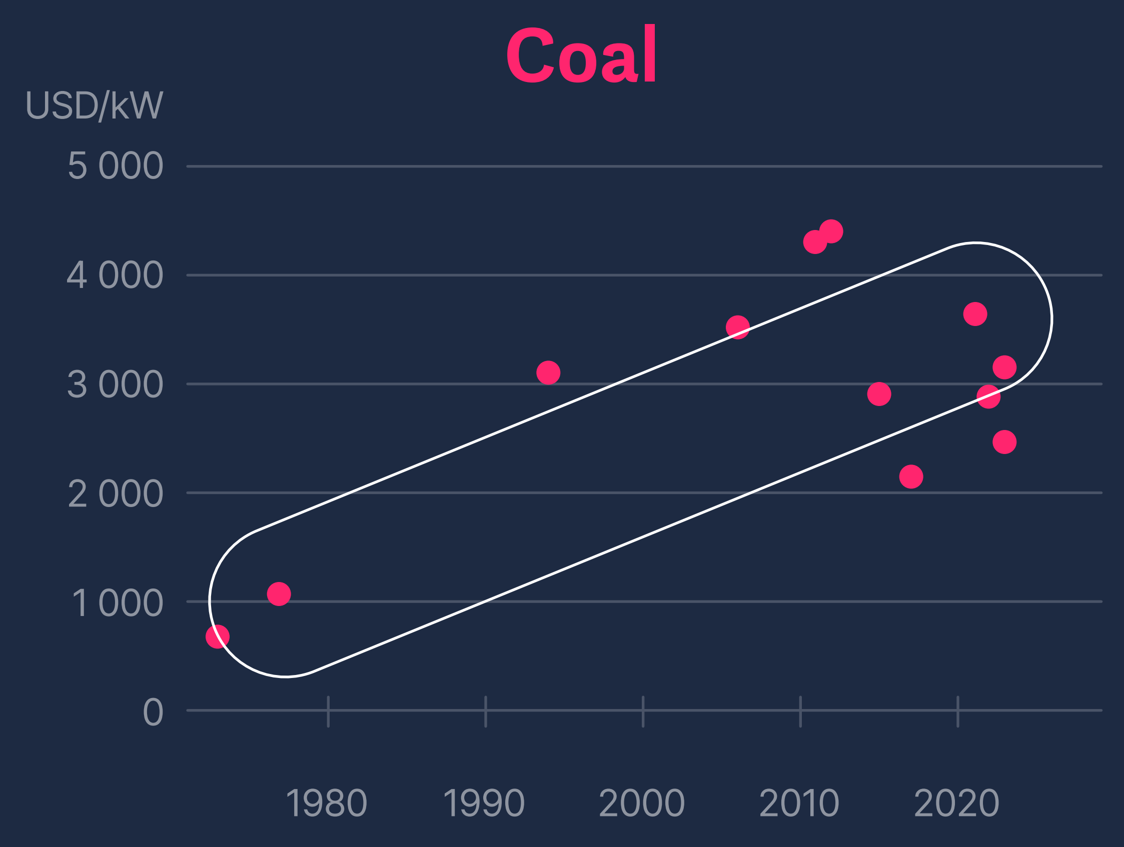
The power grid hasn't changed much.
But the economics of power generation have.

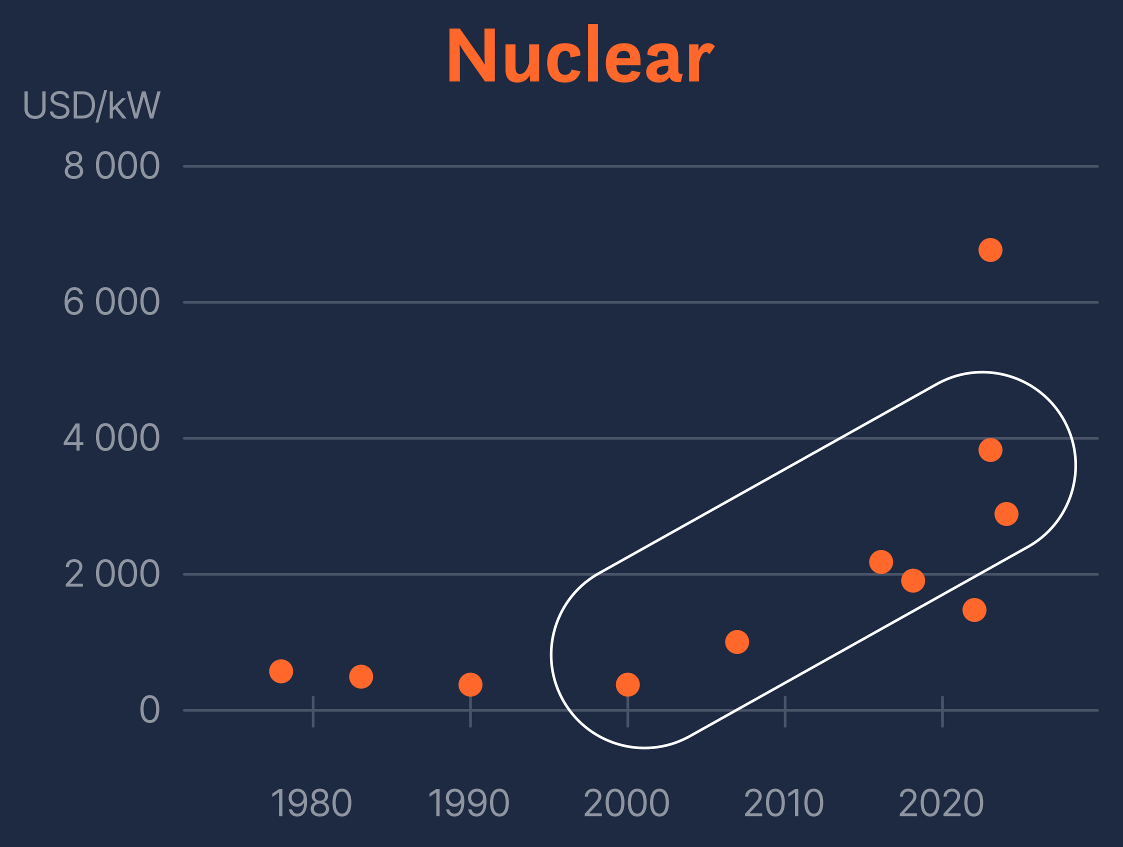
- Wind and solar are now the lowest-cost sources of new electricity supply in much of the world.[5,10]
- In addition, they are faster to build, often easier to site, and have near-zero marginal costs.

The costs of large, centralized, baseload power plants continue to go up, while the costs of renewables continue to go down

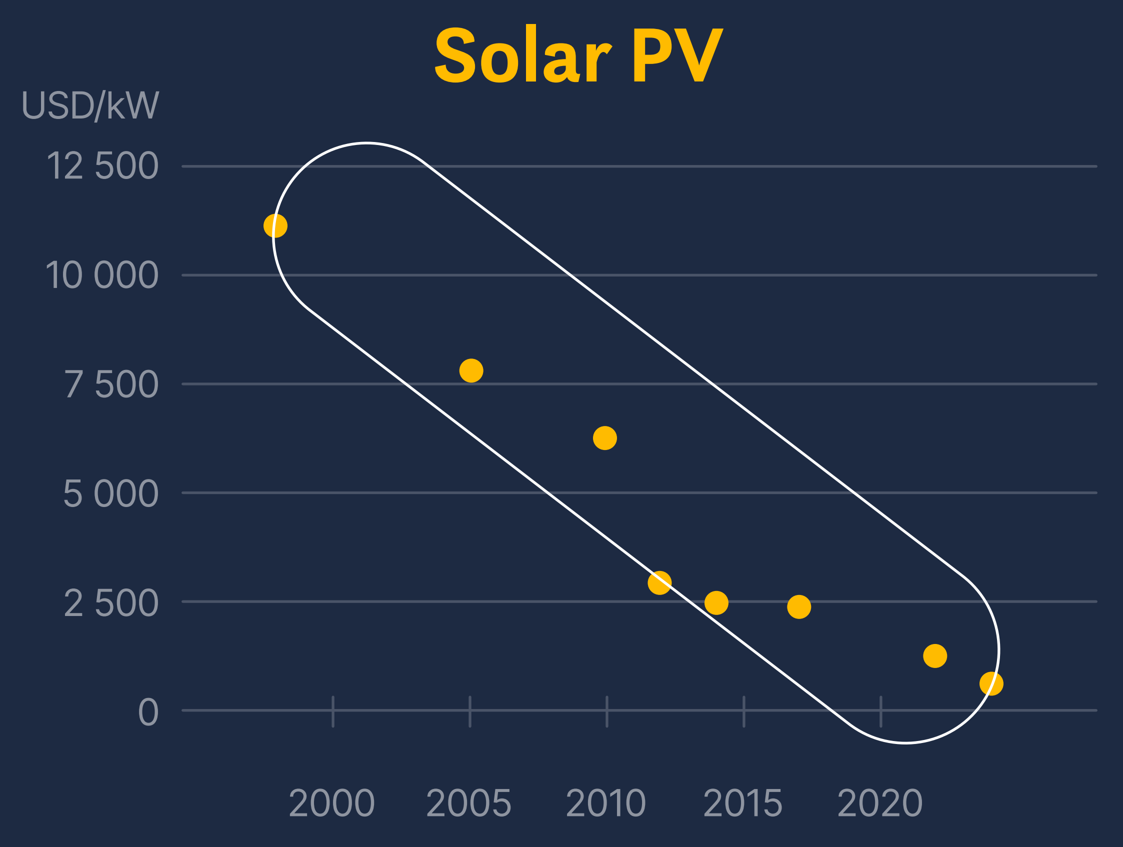
CAPEX Cost (in USD/kW) over time (adjusted to 2025). Source: E3 Analytics Research (2025).

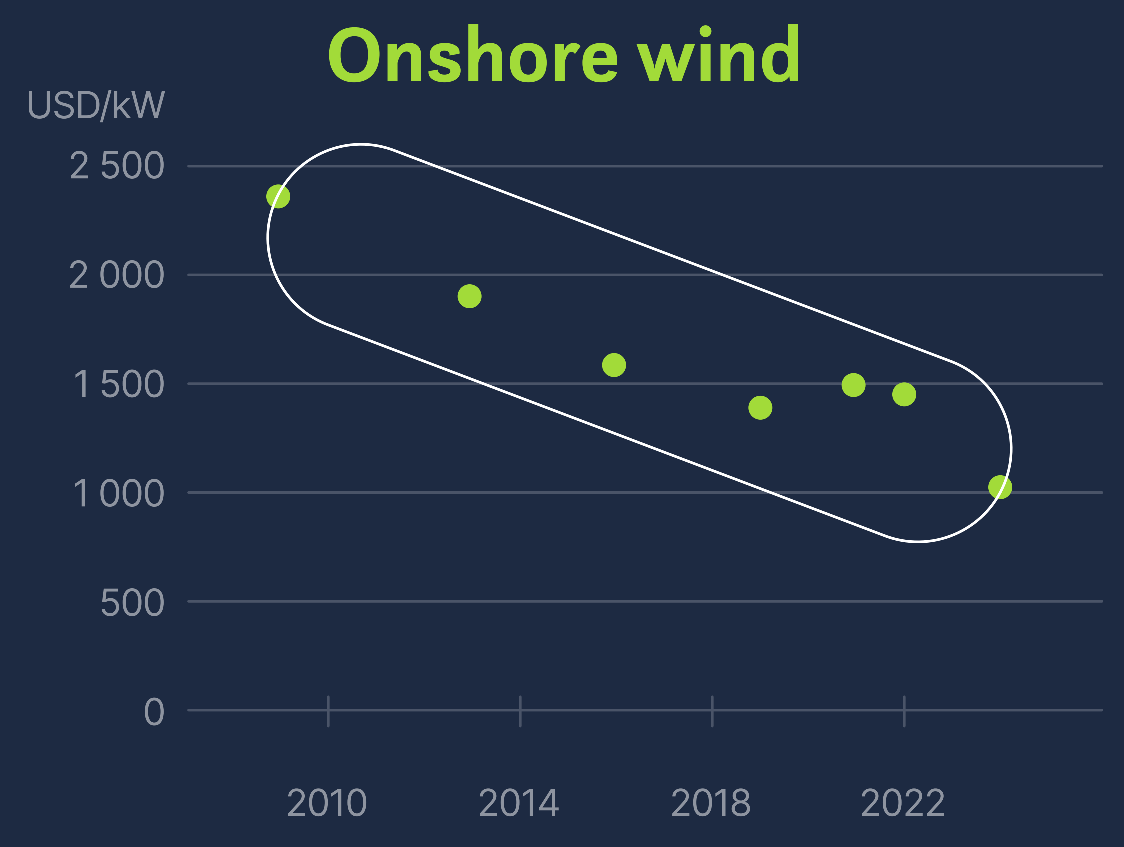
Coal and nuclear plant construction costs are rising ...





... while the costs of solar and wind continue to decline





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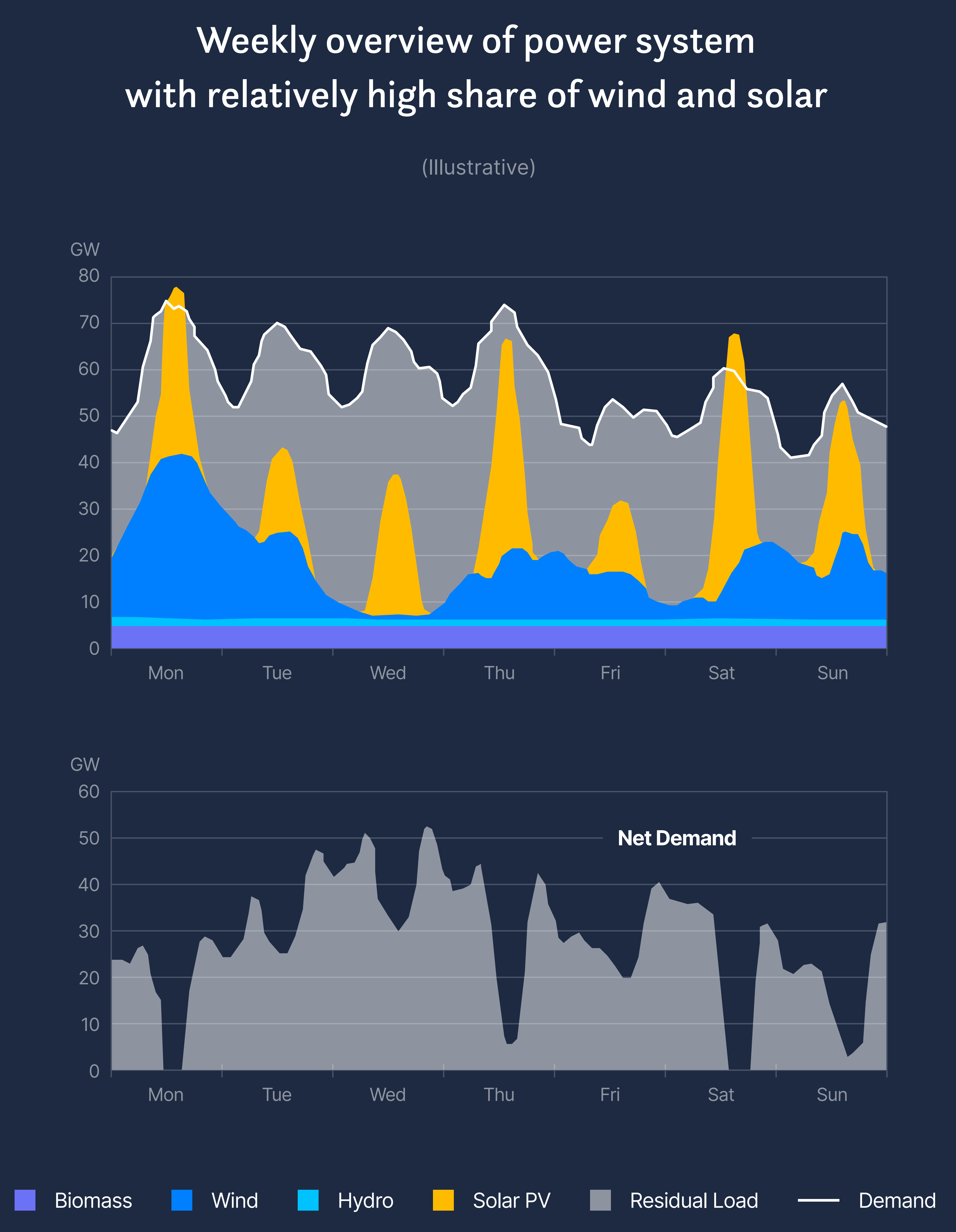
When low-cost solar and wind start to enter the system, the system starts to change

Zero Marginal Cost Renewables Disrupt the Merit Order

- Technologies like solar and wind power are dispatched first, as they have the lowest marginal cost. This reduces the hours baseload plants are needed — and their revenue.
- The shape of “net demand” (or “residual load”, i.e. what is left to be met after zero-marginal cost sources such as wind and solar have been dispatched) changes and becomes “spikier”.
- During a growing number of hours of the week, there is no room left for inflexible baseload supply.



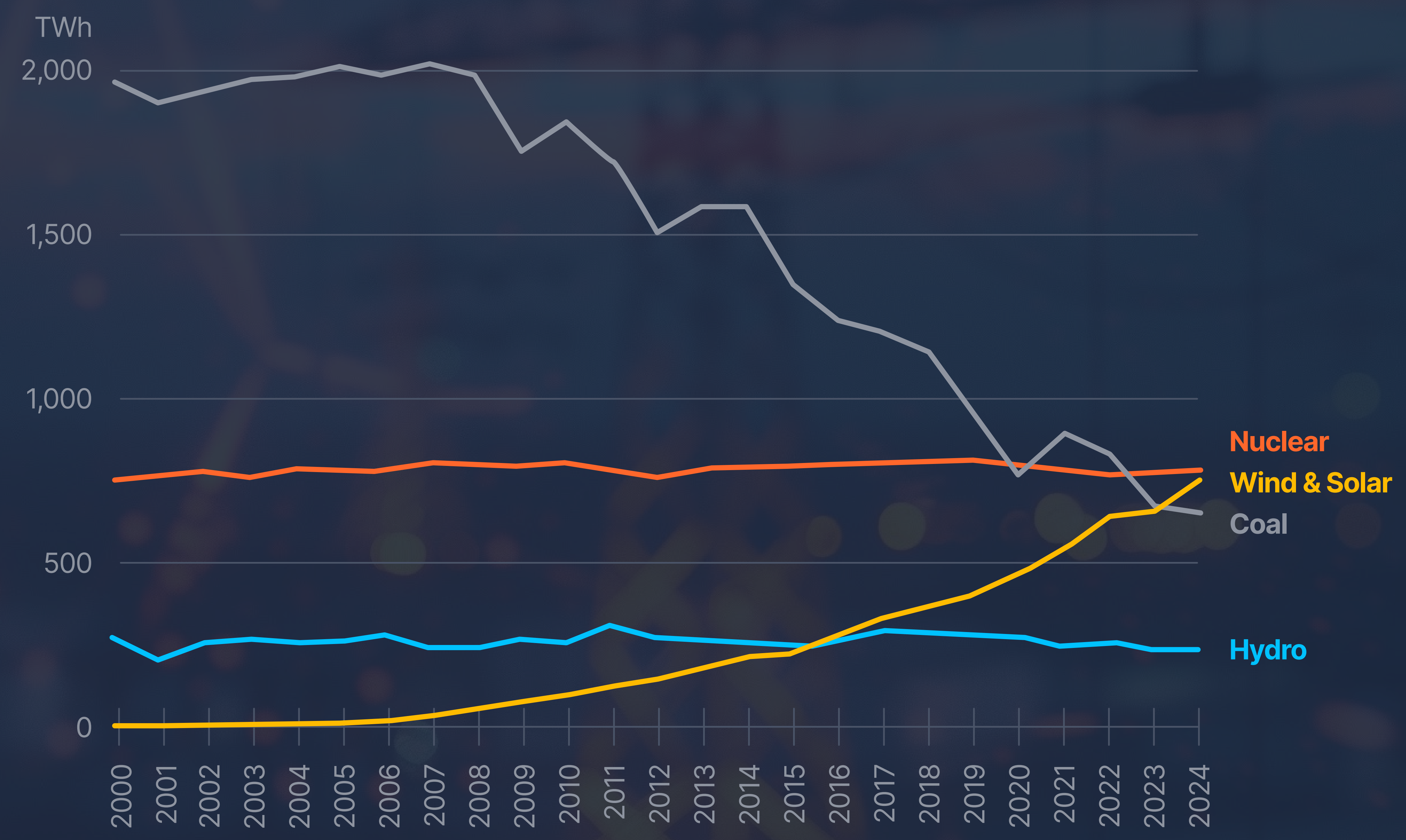
The baseload business model starts to come under strain

Lower operating hours means financial stress for baseload power plant operators

- Baseload plants were typically financed under assumptions of high, stable utilization rates.
- Reductions in operating hours mean declining revenues.
- A sustained decline in revenues can jeopardize the viability of such baseload power plants.
- The result is often calls for subsidies such as capacity payments or direct transfers to keep flagging plants alive.

US power generation from solar and wind overtake coal for the first time in 2024

Electricity generation by source [TWh]
Source: Ember[11]



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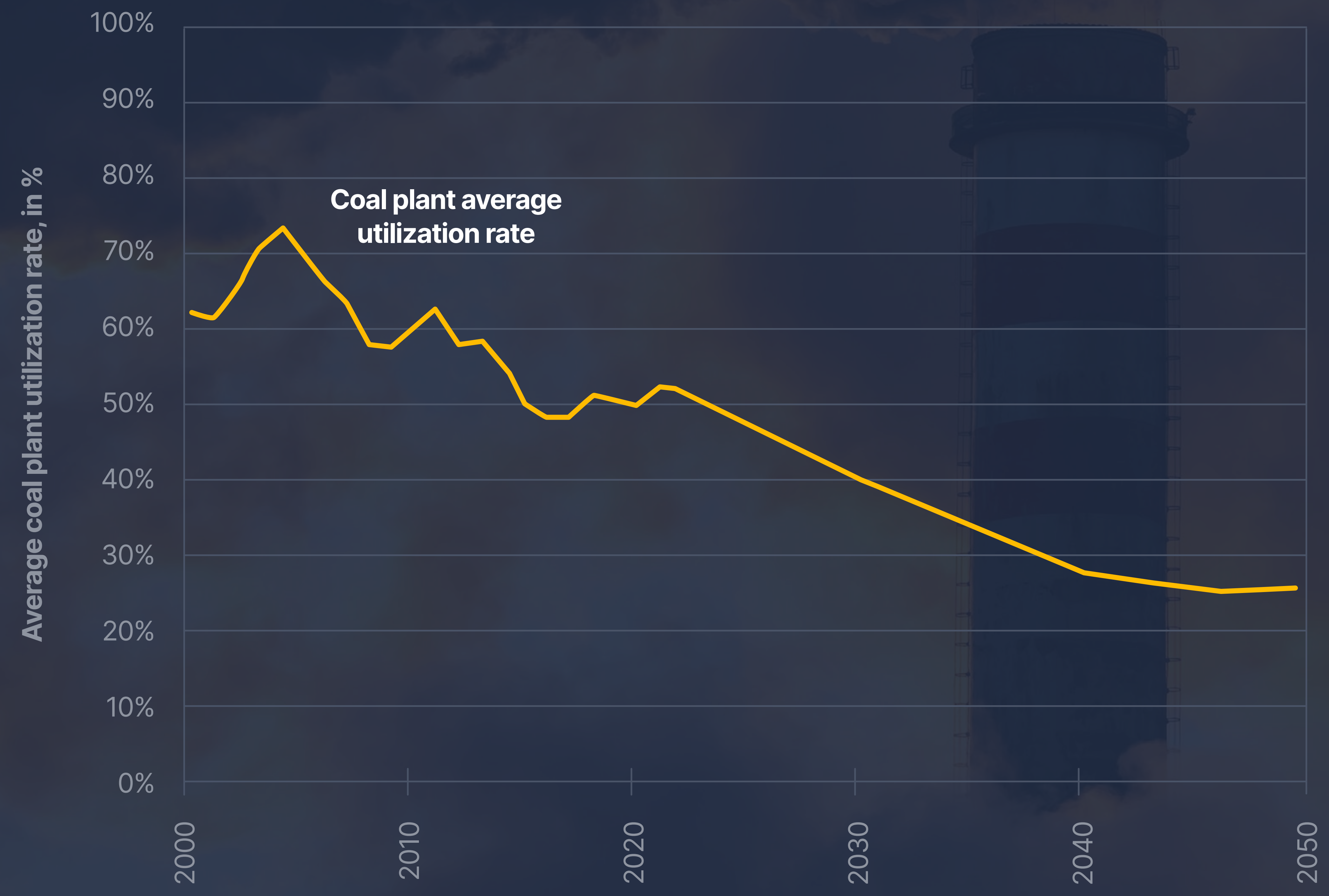
The impact on coal plant utilisation rates can be seen in China

- Coal plant capacity factors have declined from over 70% in the early 2000s to under 50% today driven largely by the rise of solar and wind.
- In response **China has recently introduced a new policy to encourage "flexibility retrofits" for its existing coal plants.**

The utilization rate of China's coal-fired power plants has been undergoing a steady decline since the mid-2000s

Source: Ritchie, H. (2024)[12]



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The fact that wind and solar are often owned by non-utility owners compounds the problem

- Wind and solar are often developed by independent power producers (IPPs).
- This means that incumbent utilities don’t control them — at the same time, utilities continue to bear the operational burden of managing and integrating them.
- The result is growing pushback from utilities and system operators.
- This pushback can be seen from countries as wide-ranging as Australia to Bulgaria, and from China to the US.

4

Political Tensions

Why incumbents resist change — and what this means for the transition away from baseload

The baseload power paradigm has become a source of significant political and economic power

Baseload systems created and sustained an interlocking set of interests — not just utilities, but also fuel suppliers, unions, investors, and other political actors.

The shift to low-cost renewables threatens that power, and the pushback is growing. Acknowledging these dynamics is essential to understanding the current debate.

Baseload power often equals political power

- In many ways, the monopoly utility and the baseload power paradigm have evolved and grown together.
- For decades, centralized, capital-intensive baseload systems were built and operated by large (often state-owned) utilities. These utilities remain politically powerful and frequently shape policy and regulation to protect their role.
- Labour unions also have a history of rallying around baseload plants, as large construction projects, jobs at local power plants, and fuel supply contracts bring major opportunities for local workers.
- The defense of the baseload paradigm is therefore about more than opposition to renewables, or about protecting aging coal and nuclear plants, or their owners. In terms of the political debate, it is often about protecting existing workers.

5

Technical Tensions

A grid built for the past meets the future

Today's technical stresses are largely a result of trying to "shoehorn" new technologies into an ageing paradigm

- **Many system operators lack the software, training, and specific skills** to manage a system dominated by wind, solar, batteries.
- **A further challenge is that grids can take decades to plan and build, while new renewables can be added in days, weeks, and months** — this means that bottlenecks can arise quickly, and can lead to a host of planning and operational challenges.

Grid operators are trained to protect the system, not transform it

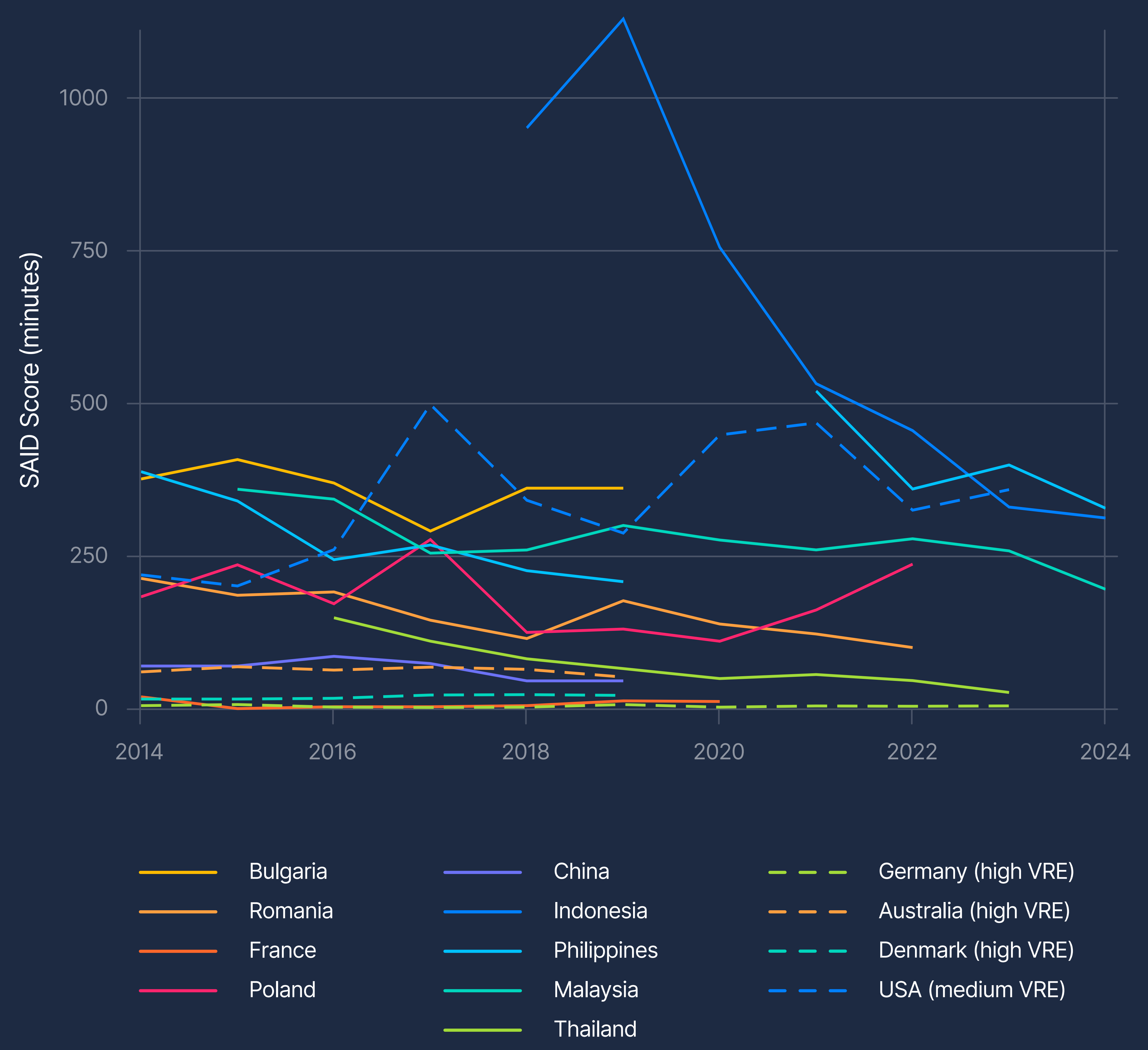
- **System operators are rightly cautious.** Their job is to keep the lights on, and they have been trained to operate a paradigm centered on large, centralized, synchronous generation and largely passive, forecastable demand.
- Their aim is to prioritize reliability above all else.
- The result is that among those tasked with maintaining the reliability of the power system, **operational conservatism runs deep**.

While intuitively plausible, the thesis that more baseload power means a more reliable power system is not supported by the evidence

- Solar, wind, and batteries do not behave like coal and nuclear plants: together, however, they are demonstrating that they can deliver the same or even higher power system reliability.
- Countries with high shares of solar and/or wind power like Germany, Denmark, and Australia consistently exhibit higher reliability than countries with far lower shares.
- Meanwhile, baseload-dominant countries like France, Bulgaria, and Romania exhibit lower reliability than many of their European peers.

System Average Interruption Duration Index (SAIDI) Scores by Country (2014–2024)

Source: E3 Analytics Research



There is an **economically and technically viable way** of meeting society's need for affordable, reliable electricity that does not rely on baseload power.

It is going to look somewhat different in different places because of geography, the degree of interconnectedness with neighbors, local wind/solar resources, the availability of reservoir hydropower or pumped hydropower stations, as well as the differing availability of capital.

But it is possible.
In fact, it's already happening.

6

The emergence of a new paradigm

The operation of power plants from across a host of countries across Asia, Africa, Europe and the Americas are starting to operate less and less as baseload

While countries like Germany, Australia, and Denmark are leading the shift, others like China, Chile, Hungary, Bulgaria and Poland are following suit.

The implications for how power systems are designed, planned, and operated are profound.

Investments in solar and wind power have surged in Poland in recent years

- Until 2012, solar and wind represented less than 5% of Poland's total electricity mix.
- Since then, variable renewables have grown rapidly, gradually displacing coal in the system.
- In 2024, solar and wind provided 24% of Poland's electricity generation.

The market share of solar PV and wind power in Poland continues to grow

Source: Ember Data Explorer[13]

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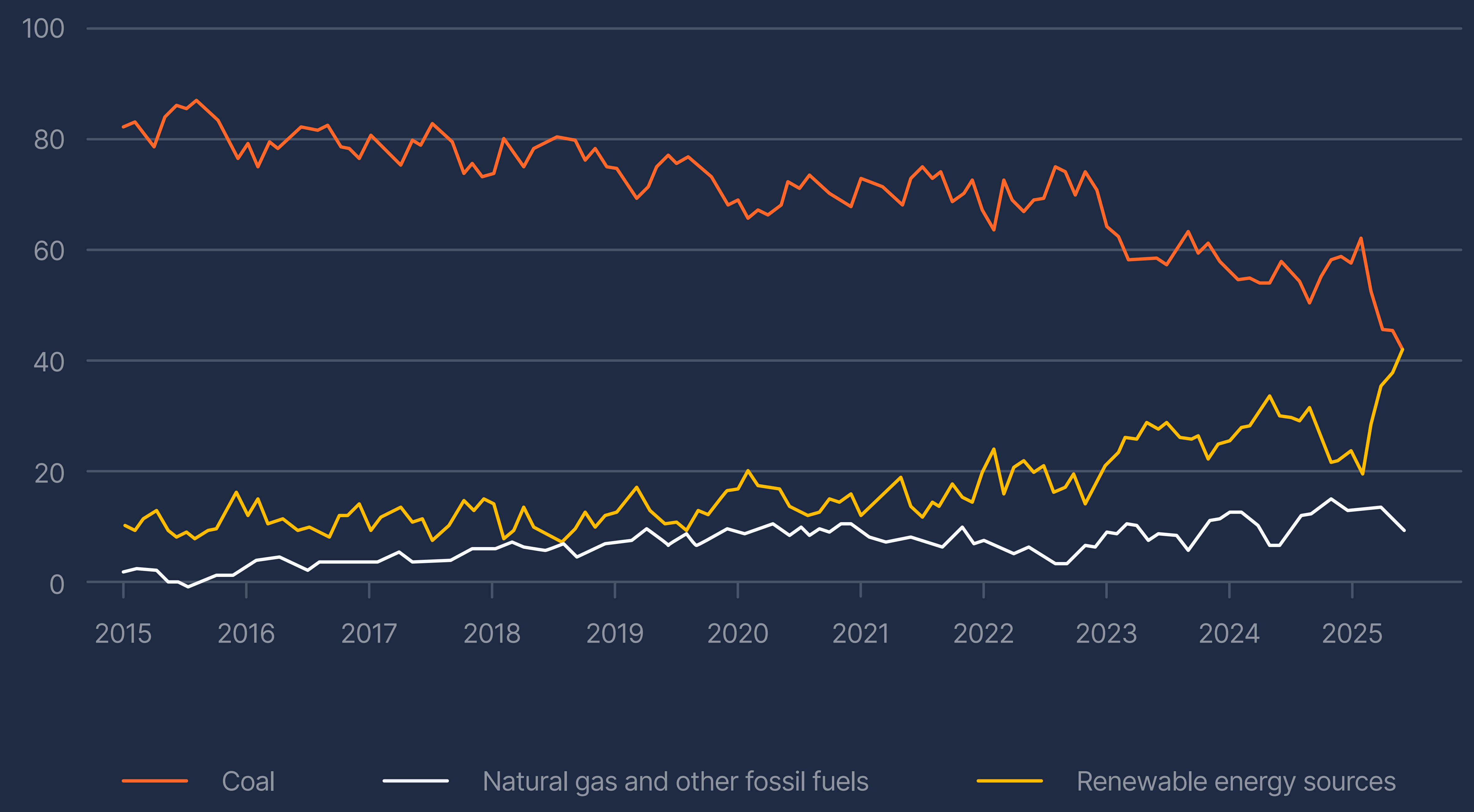
Renewable generation in Poland has overtaken coal for the first time in 2025

- The share of coal in Poland has declined from 95% in 2000 to below 50% today.
- The reduction in coal's market share in Poland is a clear sign of the magnitude of the changes now afoot.

Renewables surge as coal declines

Renewables and coal each supplied roughly 44% of Poland's power generation in June 2025.

Source: Financial Times[14]



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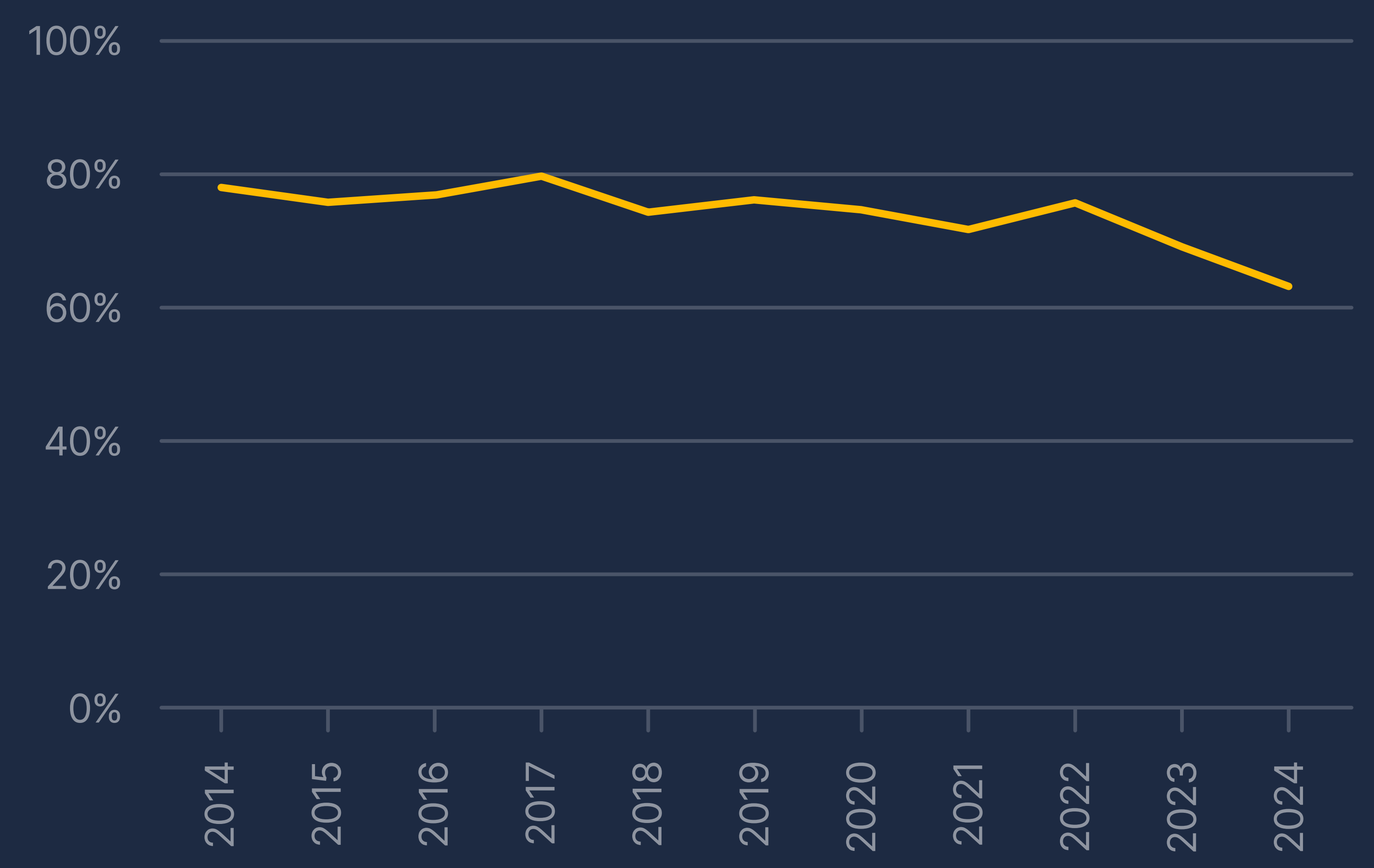
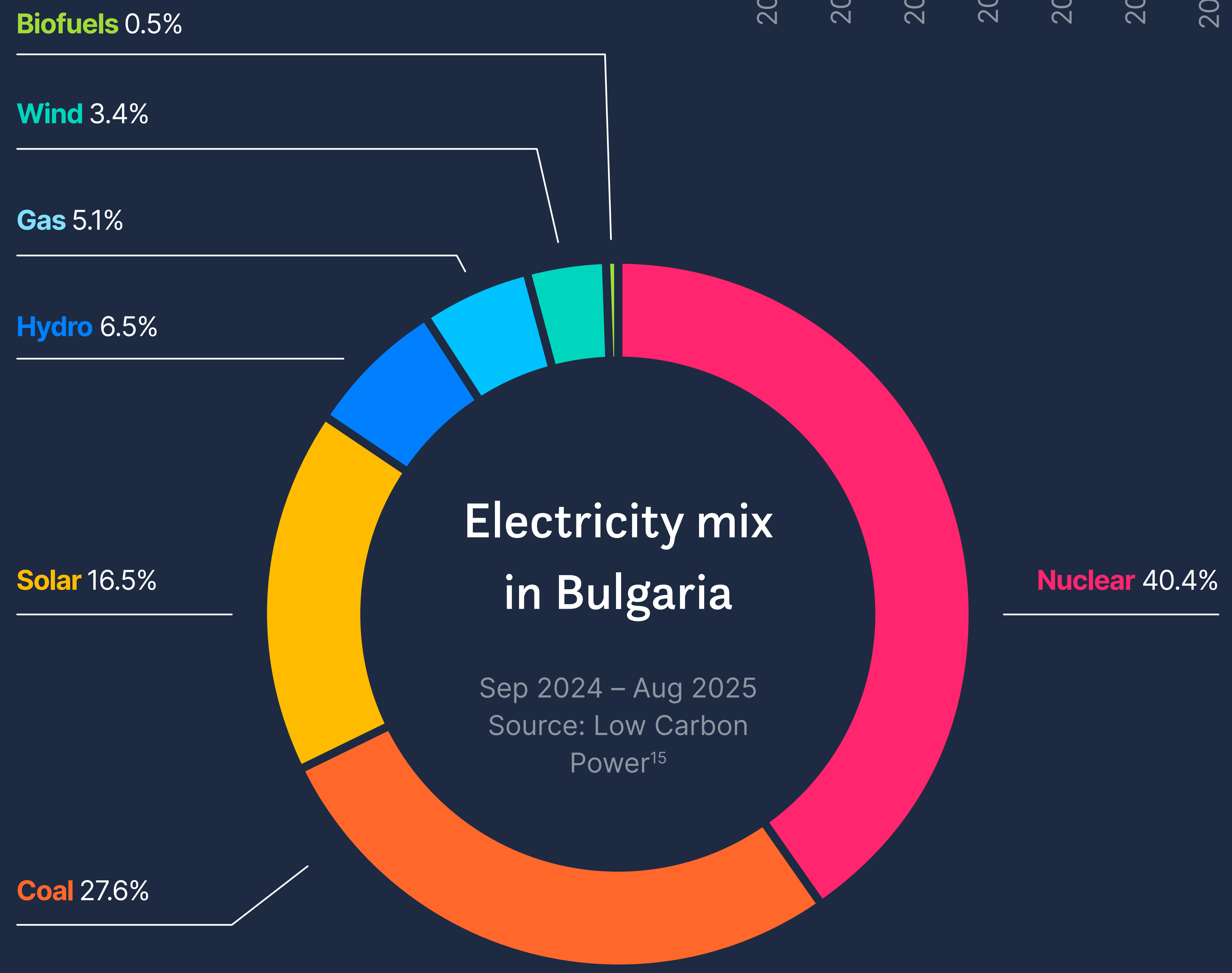
Coal and nuclear power have long been the bedrock of Bulgaria's power system

- Meanwhile, the share of solar PV in Bulgaria has surged from 1.5% in 2010 to over 18% in 2024.
- As solar grows its market share, it is generating pushback, fueling criticisms that solar power is incompatible with system reliability.
- In 2024, 63% of power supply was generated by baseload coal and nuclear plants, down from 76% in 2022.

The share of coal and nuclear is also shrinking in Bulgaria

Source: Our World in Data[16]





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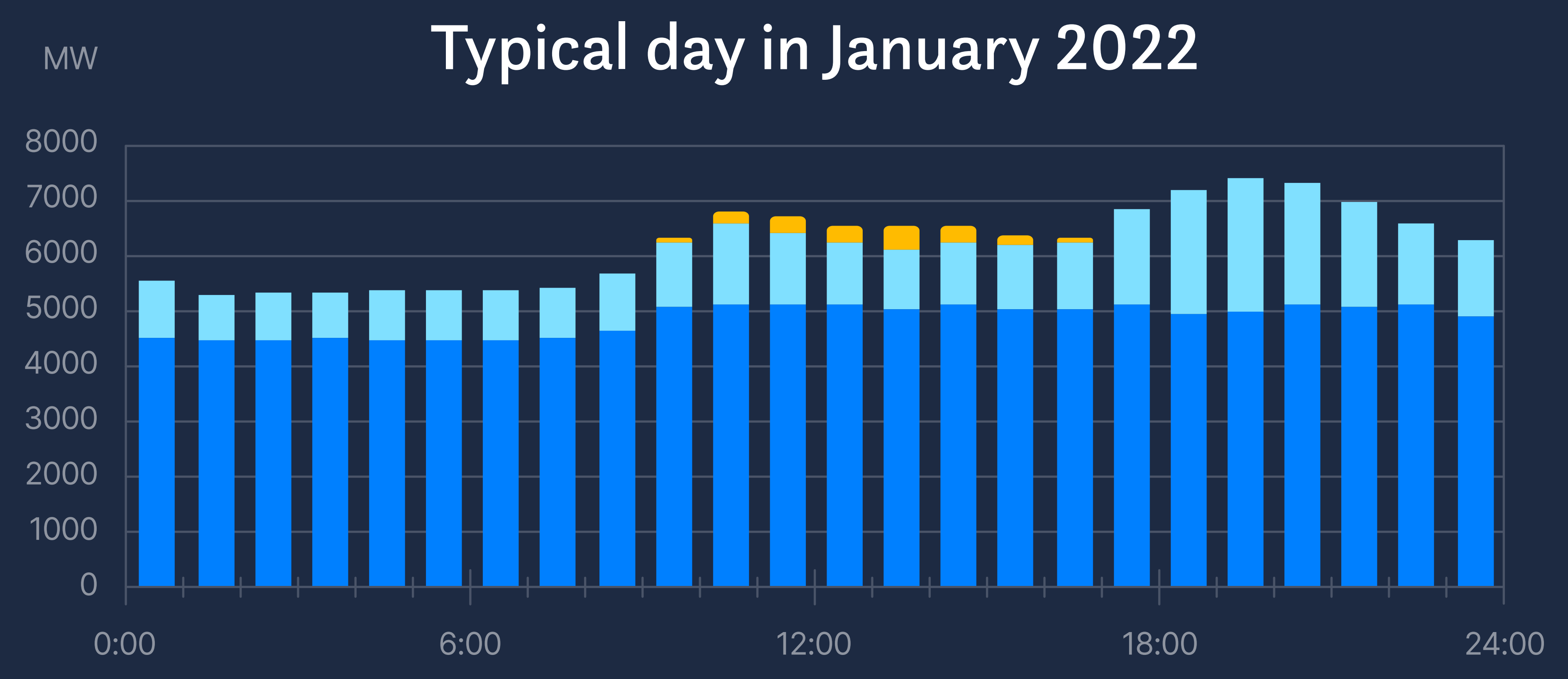
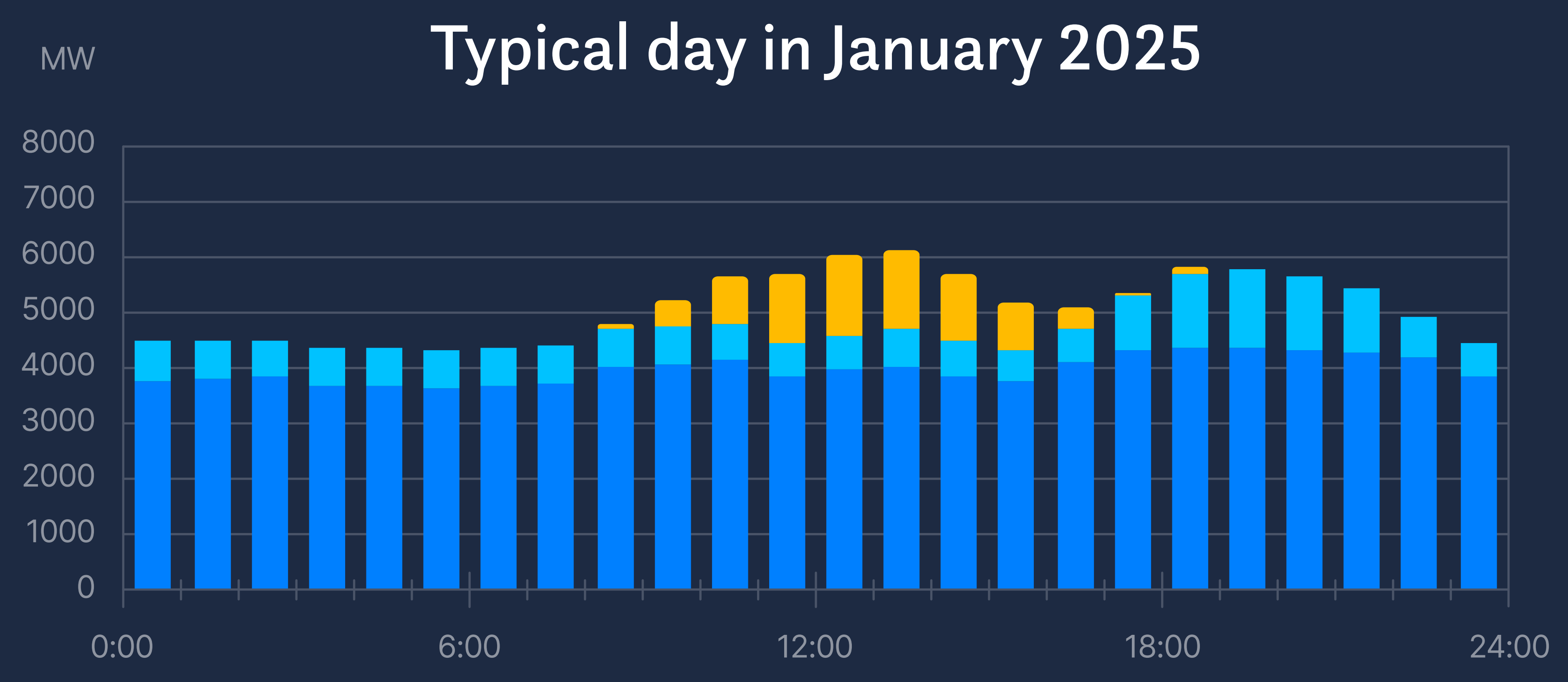
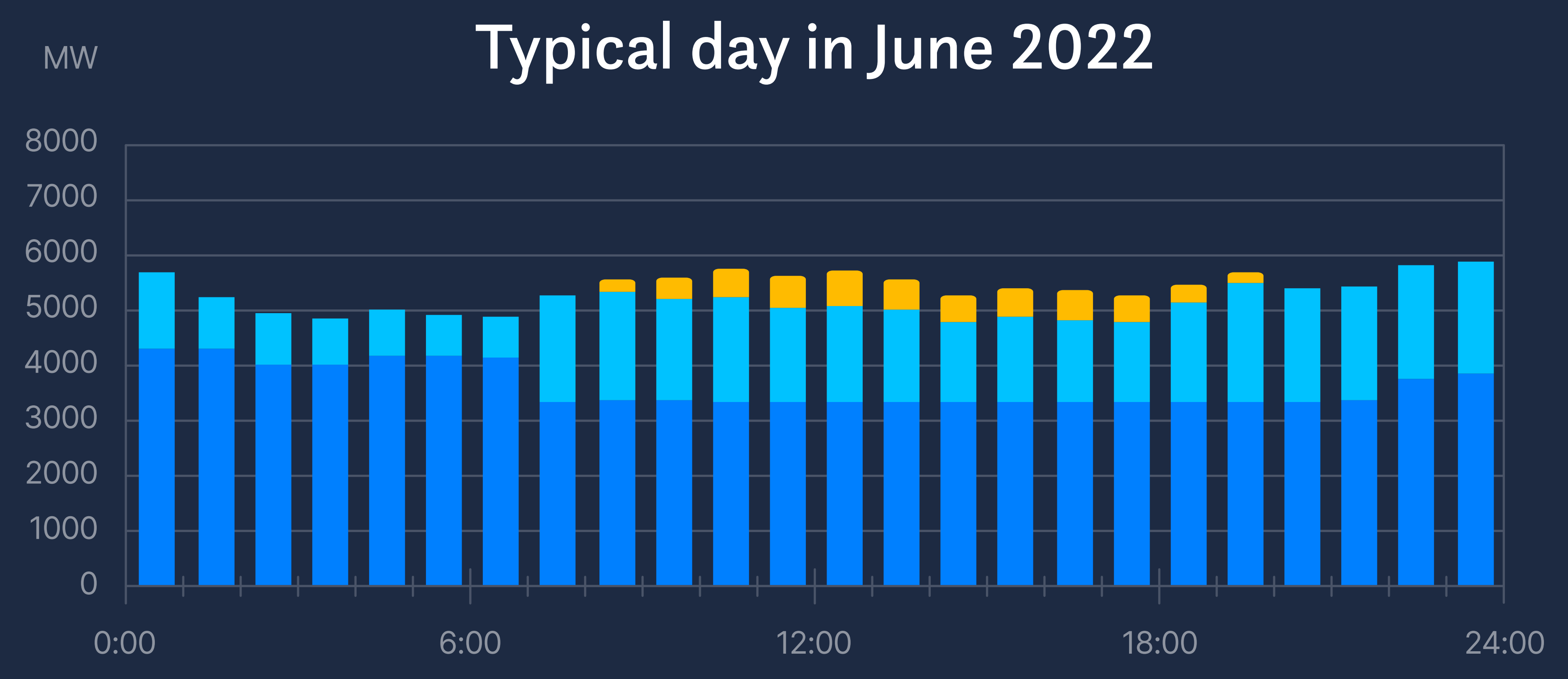
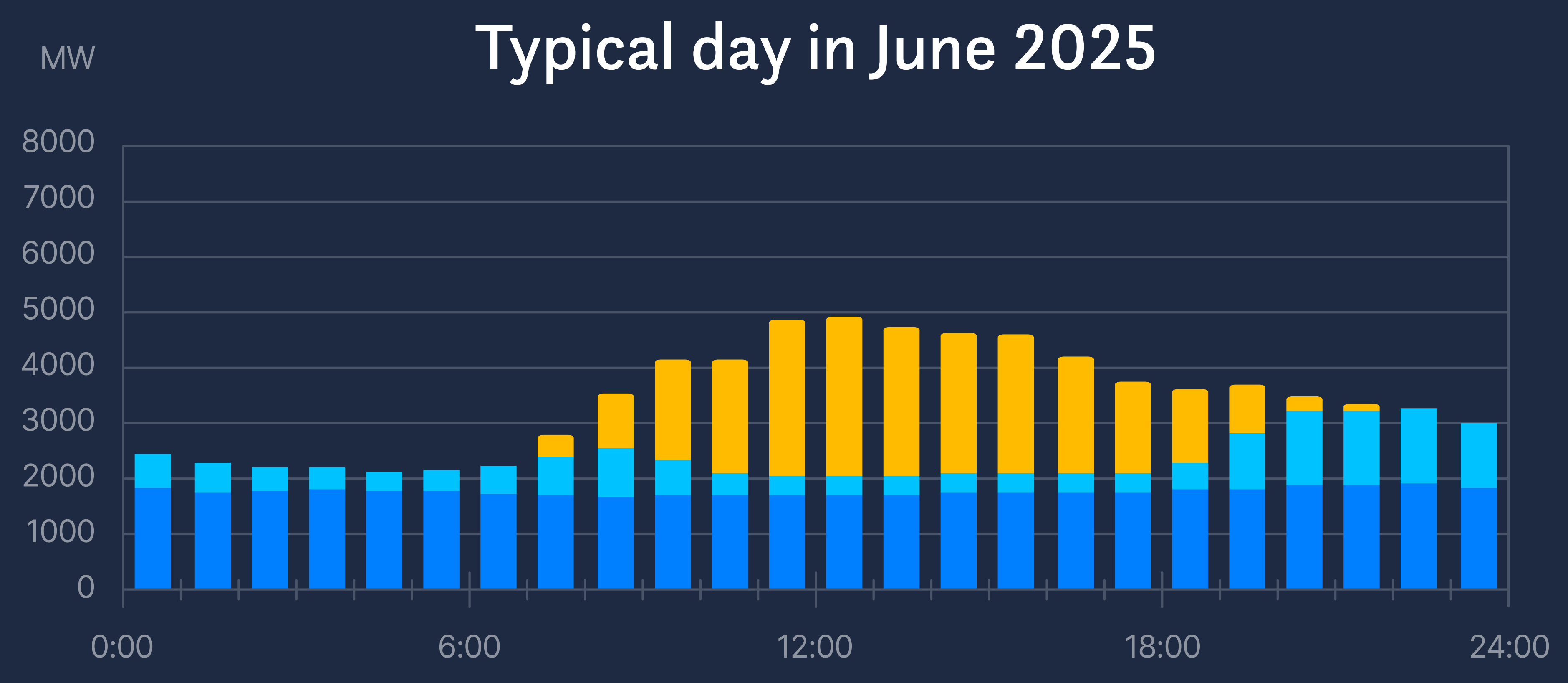
Solar power generation in Bulgaria now dominates daytime power supply, reaching over 50% of the mix during a growing number of days of the year

Source: Bulgarian Regulatory Commission[17]









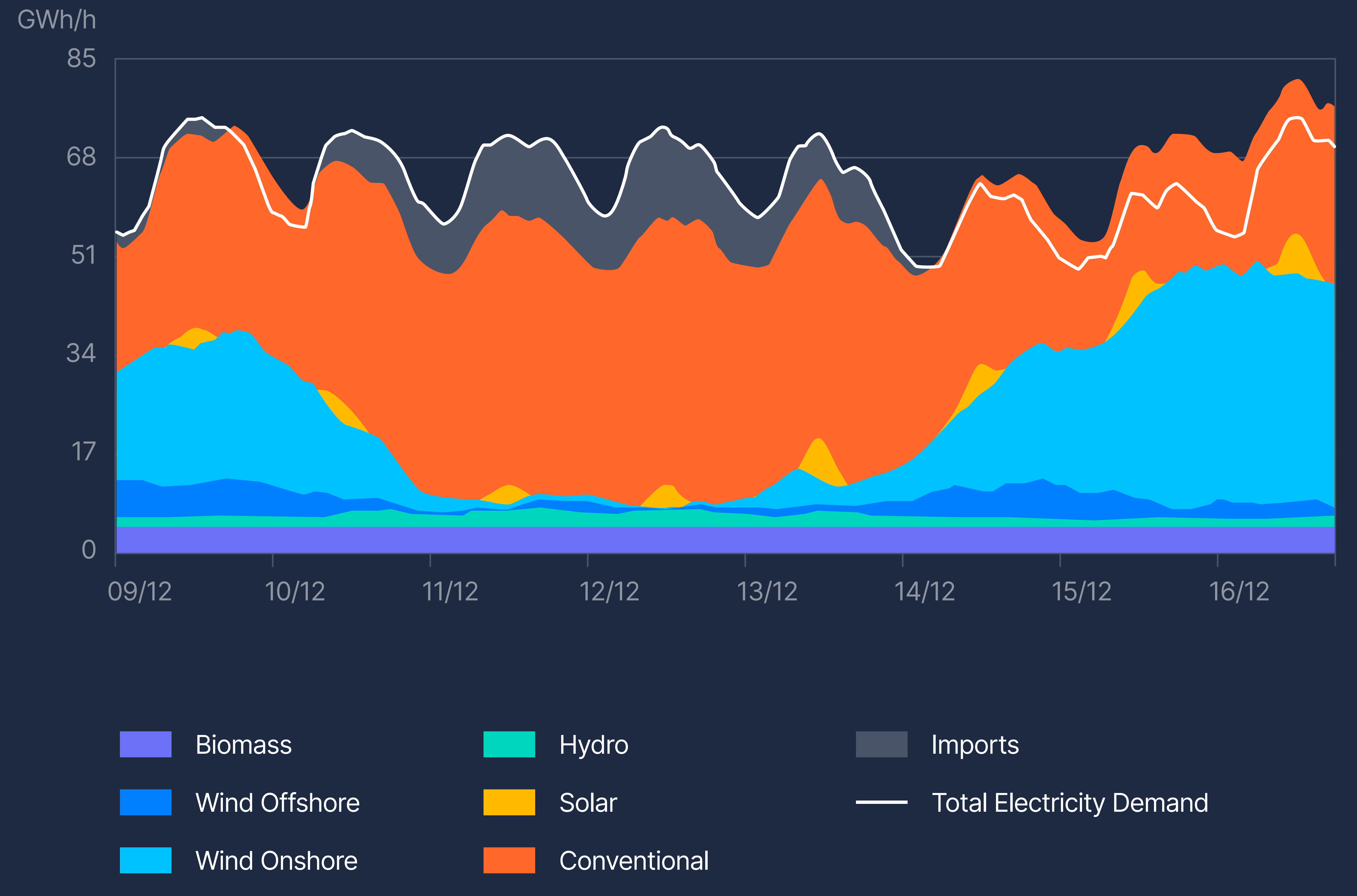
Solar | Flexible supply (gas and other) | Baseload (nuclear and coal)

One of the final frontiers remains solving the much-debated "Dunkelflaute"

- **The Dunkelflaute** refers to the recurring period of low wind + solar in countries like Germany; they typically occur 1–2 times per year and last from 2–5 days on average.[18,19]
- Considered on an annual basis, it is clear that baseload power is not the solution to the Dunkelflaute problem.
- What's needed instead is flexibility – including flexible supply, more responsive demand, expanded import capacity, and more storage.

The Dunkelflaute in Germany

Power generation and consumption, December 9–16, 2024
Sources: AGORA[20]



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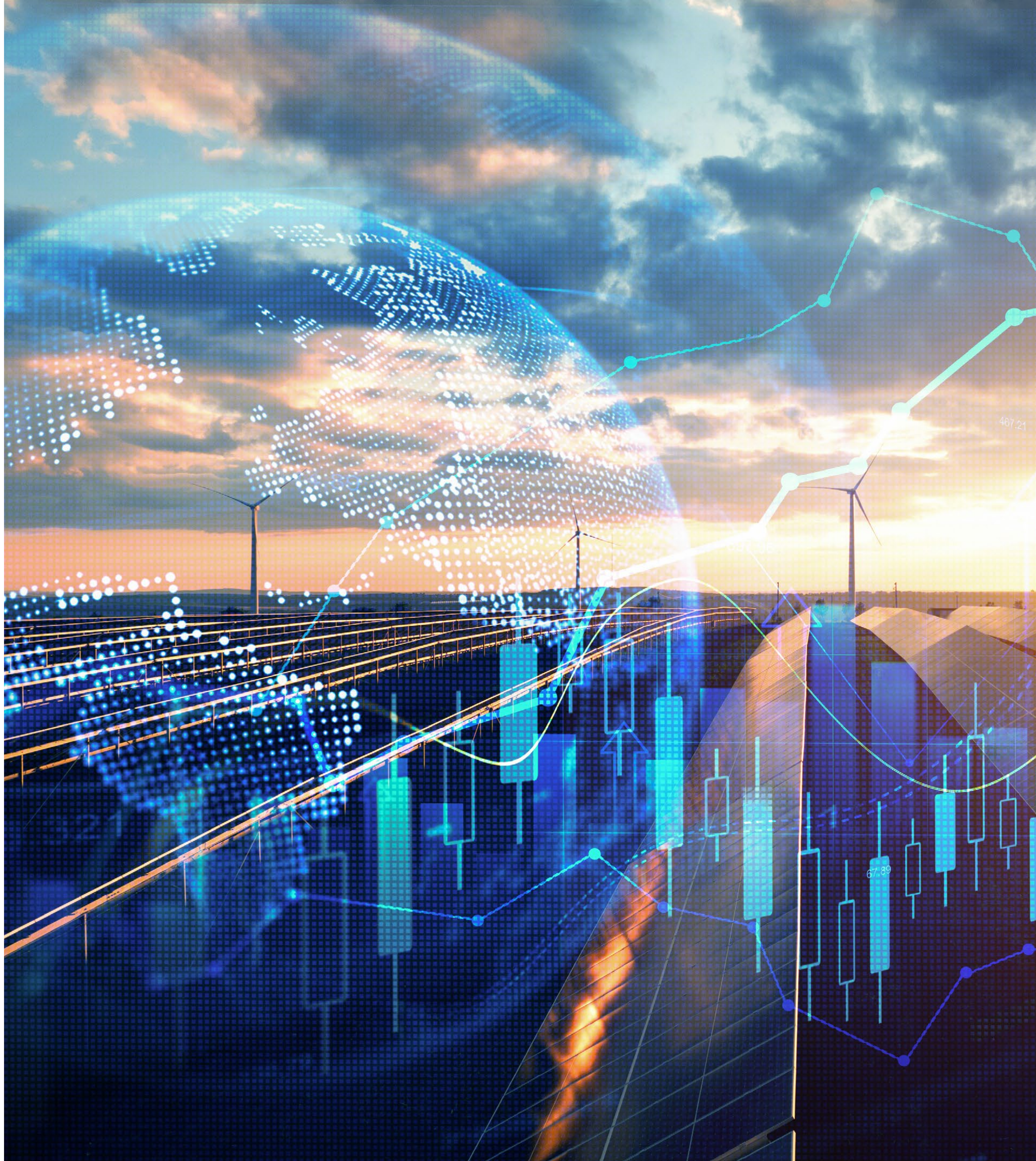
7

Can it be done?

Can a power system work without baseload power plants?

With a growing number of examples from around the world, the outlines of a new power system paradigm are starting to take shape

- The baseload paradigm has so deeply informed power system thinking that many no longer question it – like a fish unaware they are in water.
- One function of this report has been to point out the water.



Key pillars of the new power system paradigm

1 Renewables are emerging as the bedrock

Due to their low cost, VRE sources are no longer supplemental; they are becoming foundational.

Solar and wind power in jurisdictions like Australia, California, Denmark, and Germany increasingly dominate daytime power supply, leaving other resources to store, ramp and flex around them.

2 Grids are increasingly being planned around VRE

Grid planning is increasingly geared toward bringing low-cost renewables online.

Countries like India are proactively building transmission infrastructure in renewables-rich states to connect over 100GW of renewables to population centers and industrial hubs.

3 Operations are increasingly dynamic, and digital

Forecasting, machine learning, grid enhancing technologies, and AI-supported software are starting to underpin the system.

High wind countries like Denmark are relying on increasingly advanced forecasting and tools like dynamic line ratings to maintain reliability in real-time.

Key pillars of the new power system paradigm

4 System stability is being achieved through power electronics rather than large rotating masses

New approaches to manage rapid variations in supply and demand are being implemented to protect grid equipment from voltage and frequency fluctuations.

Jurisdictions like Texas and South Australia Power Networks (SAPN) are increasingly relying on fast frequency response from batteries and other inverter-based resources to balance the system.

5 Demand-side flexibility is being orchestrated alongside power supply to keep the system in balance

Dozens of countries around the world are starting to harness demand-side flexibility at scale to balance the grid.

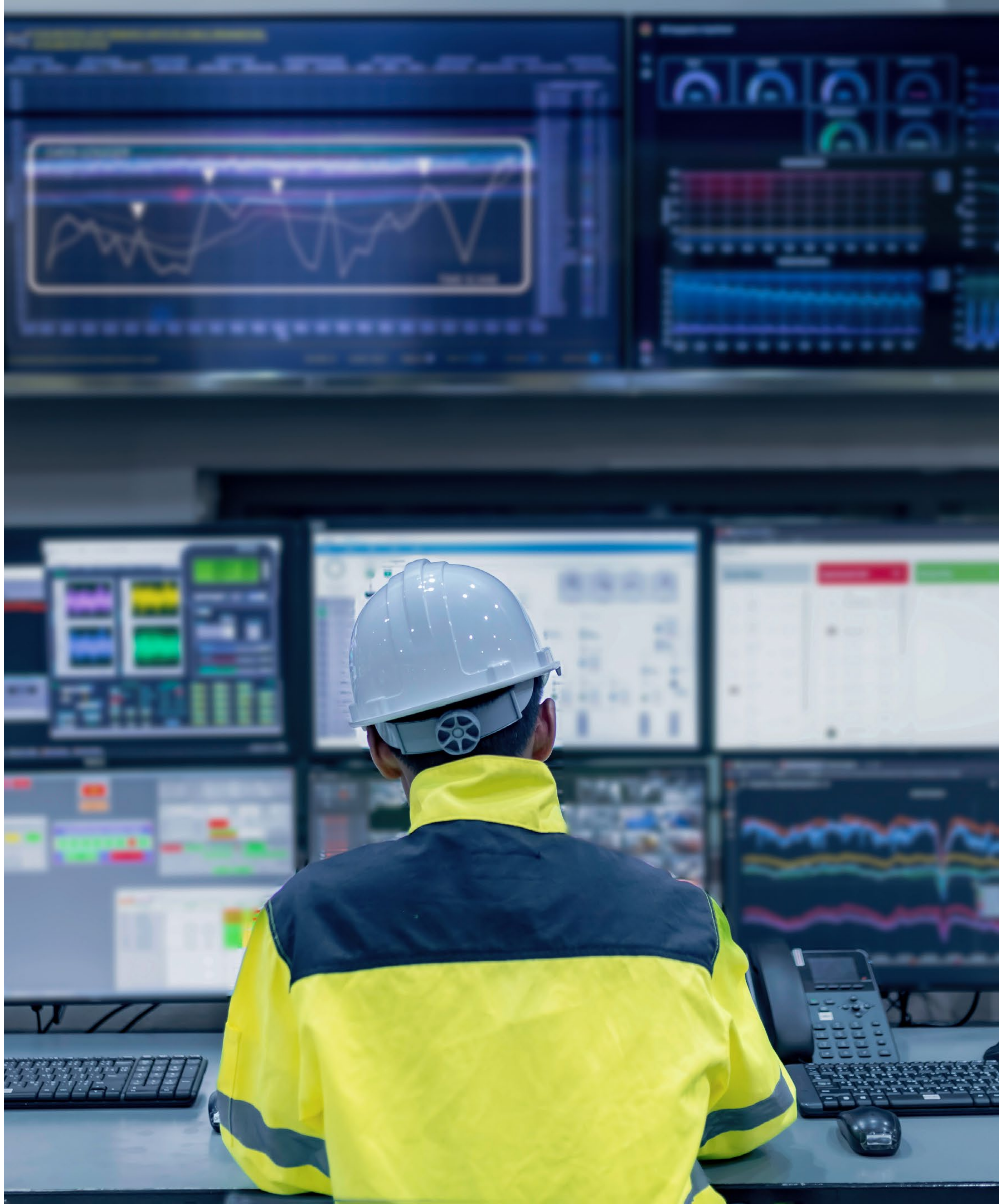
China has recently launched pilots in nine cities to harness the vast flexibility resource that exists in its electric vehicle fleet.

Economic considerations now make it smarter for low-cost solar and wind power to serve as the new foundation

- Armed with new hardware and software tools, power system operators are finding that enhancing flexibility is often cheaper than propping up inflexible baseload power plants.
- A new paradigm of power system operation is emerging, one that increasingly has variable renewables at its core.

What does this mean for utilities and grid operators?

- Traditional baseload power plants will not go out like a light.
- It is more likely that the baseload generators that can ramp their output up and down will start to do so, operating their plants more flexibly while striving to stay profitable.
- The owners of inflexible assets are likely to continue to lobby for special rules, pricing schemes, and subsidies to keep them afloat.
- Policymakers will need to decide how many subsidies should be allocated to protecting these baseload assets, versus allowing the lowest cost resources – which are now mainly renewable – to enter the system at scale.



References

1 Stone & Webster Public Service Journal, p. 311, (1907). https://books.google.co.uk/books/about/Stone_Webster_Public_Service_Journal.html?id=0O0oAAAAYAAJ

2 Leemon, A. (2025). All about that base load. https://currentlyspeaking.substack.com/p/all-about-that-base-load

3 Grist (2012). https://grist.org/renewable-energy/why-germany-is-phasing-out-nuclear-power/

4 IRENA (2025). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Jul/IRENA_TEC_RPGC_in_2024_2025.pdf

5 RMI (2023). https://rmi.org/wp-content/uploads/dlm_uploads/2023/07/rmi_x_change_electricity_2023.pdf

6 Lazard (2025). Levelized Cost of Energy+. https://www.lazard.com/media/uounhon4/lazards-lcoeplus-june-2025.pdf

7 International Hydropower Association (2023). https://www.hydropower.org/blog/providing-affordable-energy-for-generations-withhydropower

8 CleanTechnica (2025). https://cleantechnica.com/2025/03/26/92-5-of-new-power-capacity-added-worldwide-in-2024-was-from-renewables/

9 Australia Energy Market Operator (AEMO). (2022). South Australian Electricity Report, November 2022. https://www.aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/sa_advisory/2022/2022-south-australian-electricity-report.pdf

10 Ember (2025), Global Electricity Review 2025. https://ember-energy.org/app/uploads/2025/04/Report-Global-Electricity-Review-2025.pdf

11 Based on Ember (2025), US Electricity 2025: Special Report. https://ember-energy.org/app/uploads/2025/03/US-Electricity-2025-Special-Report.pdf

12 Ritchie, H. (2024), China is building more coal plants but may burn less coal. https://www.sustainabilitybynumbers.com/p/china-coal-plants

13 Ember Data Explorer (2025). https://ember-energy.org/data/electricity-data-explorer/

14 Minder, R. (July 3 2025). Poland's clean energy usage overtakes coal for the first time," Financial Times. https://www.ft.com/content/ae920241-597e-49d9-a4b9-bfdfa9deabb6

15 Low Carbon Power (2025). https://lowcarbonpower.org/region/Bulgaria

16 Our World in Data (2025). Electricity production by source, Bulgaria. https://ourworldindata.org/grapher/electricity-prod-source-stacked?time=2010..latest&country=~BGR

17 Bulgarian Regulatory Commission (2025). https://www.eso.bg/doc/?generation_per_day&date=09.06.2025

18 IMKTRO (2024). https://www.imk-tro.kit.edu/12085.php

19 EnBW (2025). https://www.enbw.com/unternehmen/themen/netze/dunkelflaute.html

20 Agora Energiewende (2025). Agorameter, December 9-16, 2024. https://www.agora-energiewende.de/daten-tools/agorameter/live/chart/power_generation/09.12.2024/16.12.2024/hourly

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