REN21

RENEWABLES 2024
GLOBAL STATUS REPORT

ENERGY SYSTEMS AND INFRASTRUCTURE

2024

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FOREWORD

Renewable energy generation is part of a broader energy system that relies on specific infrastructure to ensure energy flows efficiently from generation to consumption. Shifting to renewables demands urgent attention to this system, requiring us to rethink how we operate transmission and distribution infrastructure, manage flexibility and storage, and link the power sector with end-use sectors like transport and heating.

We must address these issues to accelerate the deployment of crucial infrastructure and technologies, secure investment, resolve existing and future bottlenecks and plan energy infrastructure to avoid resource overuse and environmental impacts. Doing so will ensure the system meets citizens' energy needs, increasing societal support for the transition.

Addressing misinformation about renewables-based power grids' ability to ensure a 24/7 electricity supply is equally important. Integrating high shares of renewables in power grids is possible, and technical solutions exist. Several countries have reached 100% renewables in the daily operation of their electricity systems, and 12 countries have successfully integrated up to 67% of variable renewables on a yearly average. However, achieving this requires forward thinking, political vision, integrated planning and substantial upfront investments.

This fourth module of the Global Status Report 2024 – Energy Systems and Infrastructure – covers recent trends and developments in policies, deployment and technological advances related to grid capacity and stability, curtailment of renewables, regional interconnections, energy storage, demand-side management and sector coupling.

As we celebrate recent commitments to renewable energy deployment and assess the road ahead, we must ensure durable policy frameworks and unlock the necessary investments. Recognising the central role of energy infrastructure and integrated cross-sectoral planning while tracking global and regional developments is crucial.

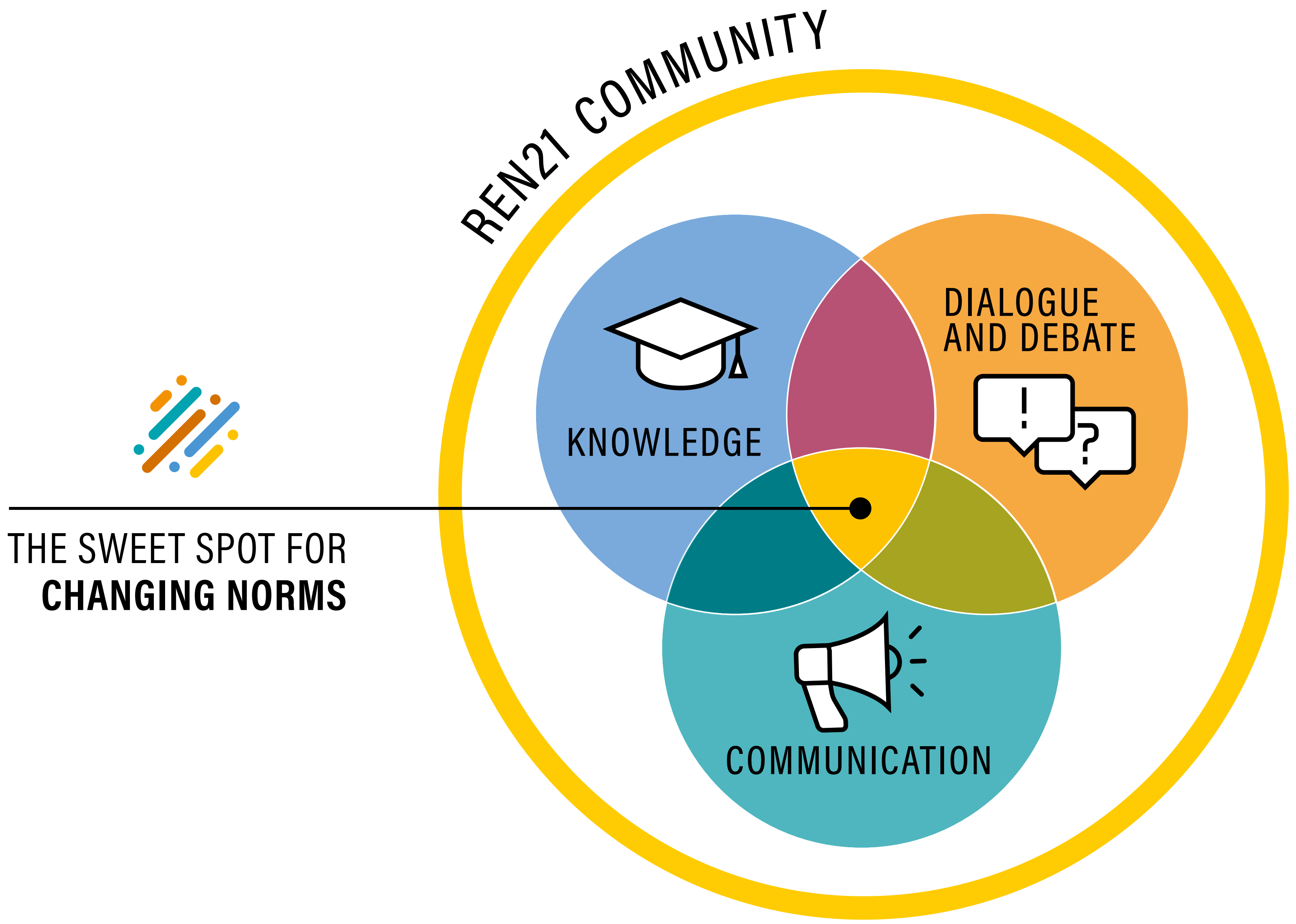
I want to thank the REN21 team, authors, special advisers, contributors and the entire REN21 community for their expertise and time in producing this module. I trust that this module will provide the insights needed to empower policymakers, industry leaders and stakeholders to fast-track the energy transition with renewables.

Sincerely,

Rana Adib
Executive Director, REN21

REN21
RENEWABLES NOW

RENEWABLE ENERGY POLICY NETWORK
FOR THE 21st CENTURY



REN21 is unique. It is the only global, **multi-stakeholder network** dedicated to renewables.

We create an **enabling environment to support renewable energy uptake**. Together, we build knowledge, shape dialogue and debate, and communicate this information to strategically drive the deep transformations needed to make renewables the norm.

Shifting to renewables is more than a fuel switch; it requires engaging with market players and society at large. **REN21 works in close co-operation with its community**, providing a platform for all stakeholders to engage and collaborate.

Through these collective efforts, REN21 builds bridges and amplifies positive and sustainable energy solutions. Our goal: enable decision makers to **make the shift to renewable energy happen – now.**

20 YEARS OF REN21

This year marks two decades since the inception of REN21 – an opportunity to celebrate 20 years of instrumental contributions to the advancement, shaping and understanding of renewable energy worldwide. Established in 2004, REN21 emerged from the collective vision of global pioneers who convened to call for accelerated commitments towards renewable energy adoption. For two decades, REN21 has been pivotal in elevating renewables to the forefront of global agendas for leaders and decision makers across all stakeholder groups, enabling knowledge exchange, dialogue and debate about the global transition to renewables.

The 20th-anniversary celebration of REN21 is also the occasion to acknowledge REN21's flagship knowledge product, the *Renewables Global Status Report (GSR)*. Since the GSR's first release in 2005, REN21 has published 18 editions of the report, crafted annually with the most up-to-date insights, facts and stories from thousands of contributors spanning diverse regions and sectors. The GSR has been central to fulfilling REN21's mission, becoming a reference for many and positioning REN21 as the global trusted voice on renewables.

20 YEARS OF CROWD-SOURCED, CROWD-OWNED KNOWLEDGE AND DATA

REN21's data and knowledge collection method is unique, drawing upon the organisation's global multi-stakeholder community of experts. Contributors from across the globe are invited to submit data, insights and stories on annual developments in renewable energy technologies, market trends, policies and local perspectives, resulting in a comprehensive and diverse dataset. REN21 performs rigorous data validation and fact-checking throughout the development of the GSR, ensuring accuracy and reliability.

Validation of the data is a collaborative and transparent process conducted through open peer reviews. Collectively, hundreds of experts contribute to making the GSR one of the most authoritative and comprehensive publications in the field of renewables. Alongside its wealth of key facts and figures, the GSR is openly accessible, fostering a shared language that shapes the sectoral, regional and global debate on the energy transition.

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for Economic Affairs
and Climate Action

Federal Ministry
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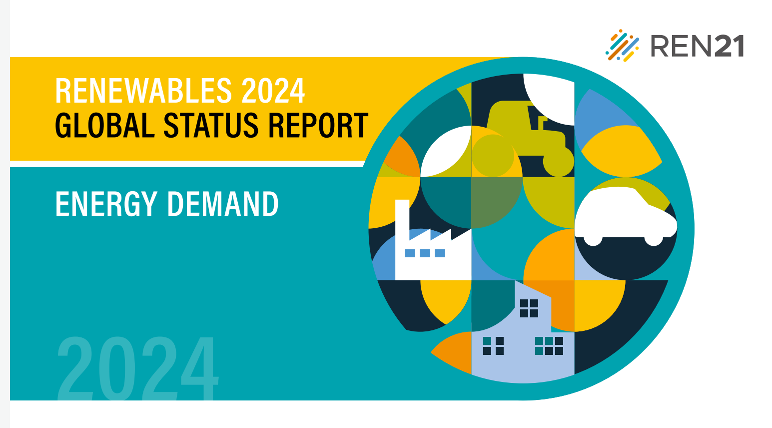
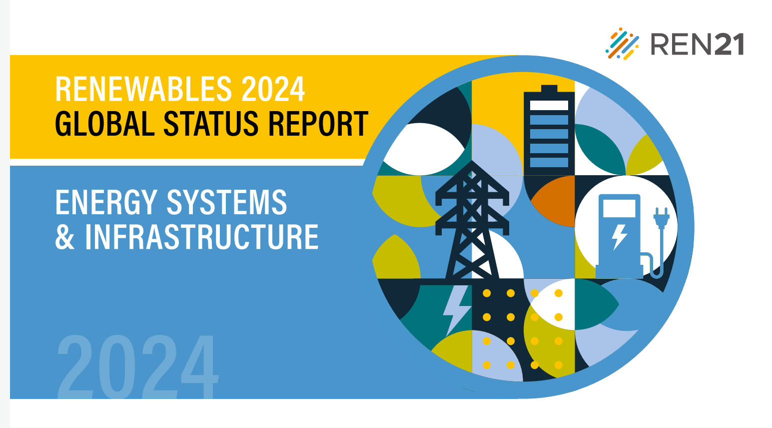
A large share of the research for this report was conducted on a voluntary basis.

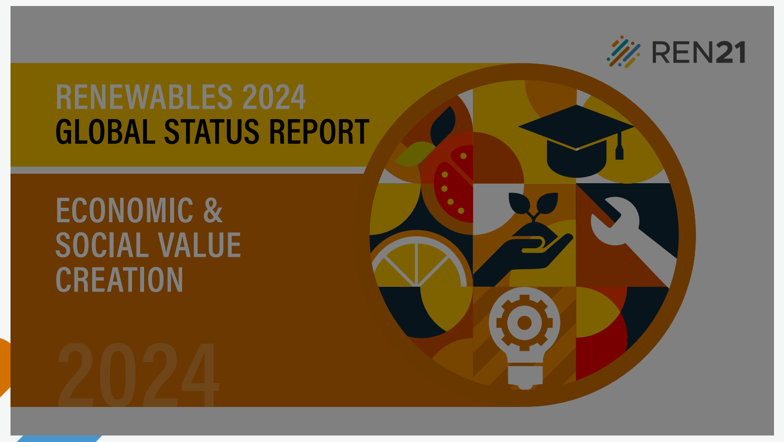
RENEWABLES GLOBAL STATUS REPORT
2024 COLLECTION

Since 2005, REN21's Renewables Global Status Report has spotlighted ongoing developments and emerging trends that shape the future of renewables. It is a collaborative effort involving hundreds of experts. Structured as a collection of five publications, this year's 19th edition of the GSR reflects key trends in global energy.

In addition to presenting the latest developments in renewable energy systems and infrastructure, the GSR provides a global overview of the renewables landscape and dives into different energy demand sectors, with dedicated modules on buildings, industry, transport and agriculture. The collection further includes a publication on renewable energy supply as well as a publication on renewables for economic and social value creation, acknowledging the key benefits of renewables for economies and societies. Collectively, these five publications offer readers a systemic global overview of the current uptake of renewables.







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ENERGY SYSTEMS AND INFRASTRUCTURE

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For further details and access to the report, references and endnotes, visit **www.ren21.net/gsr-2024**

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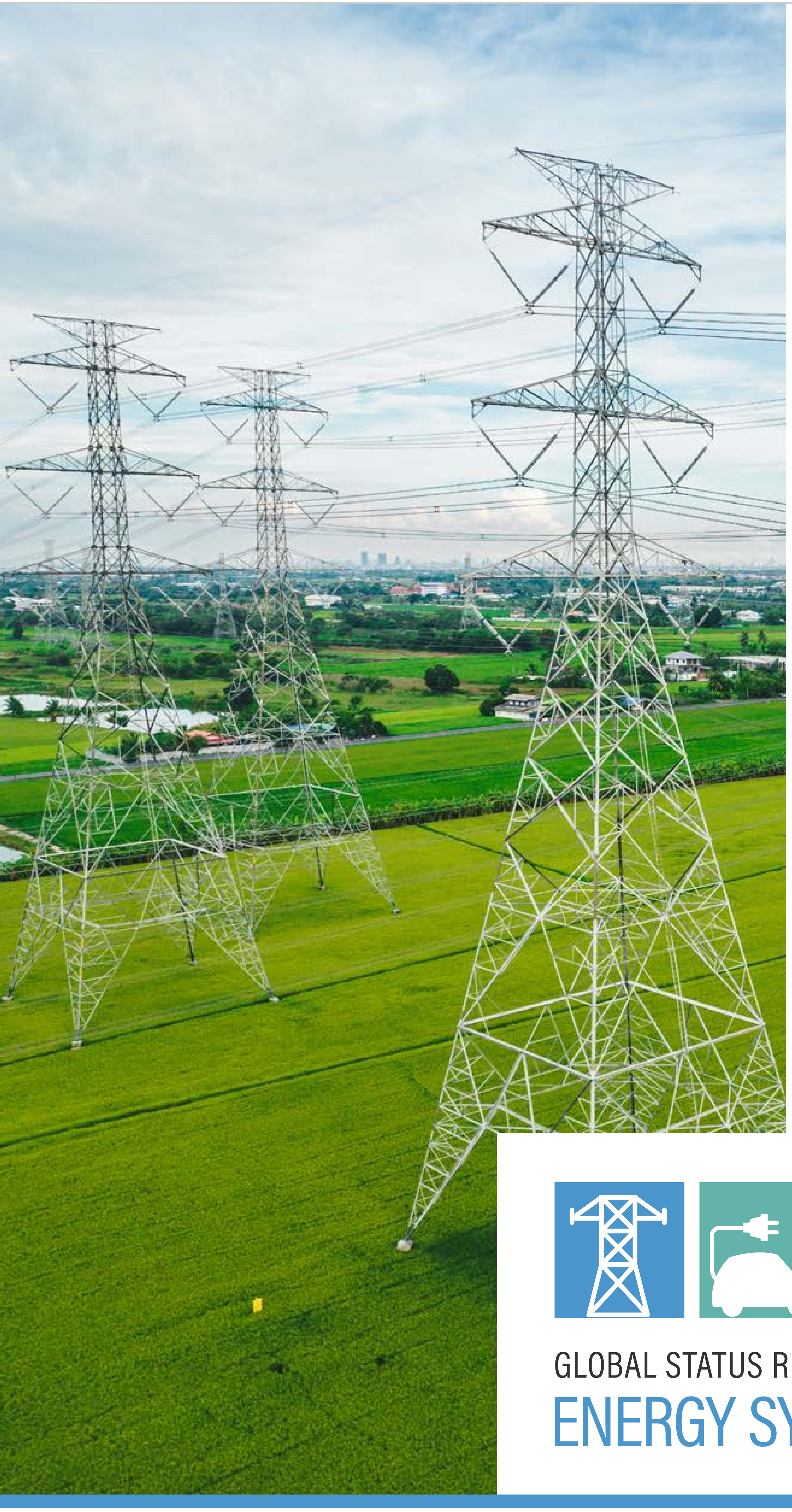

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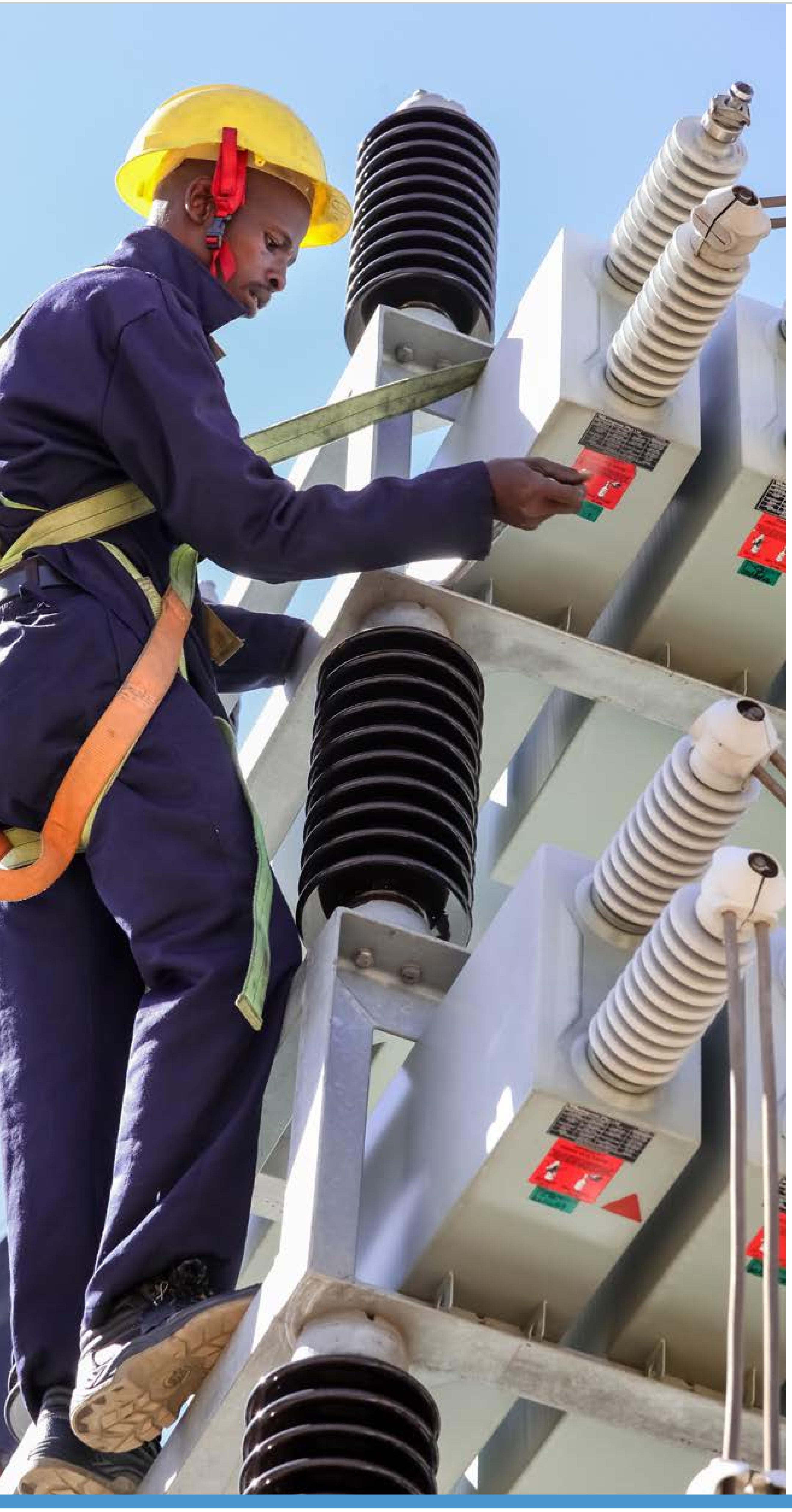

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ENERGY SYSTEMS AND INFRASTRUCTURE

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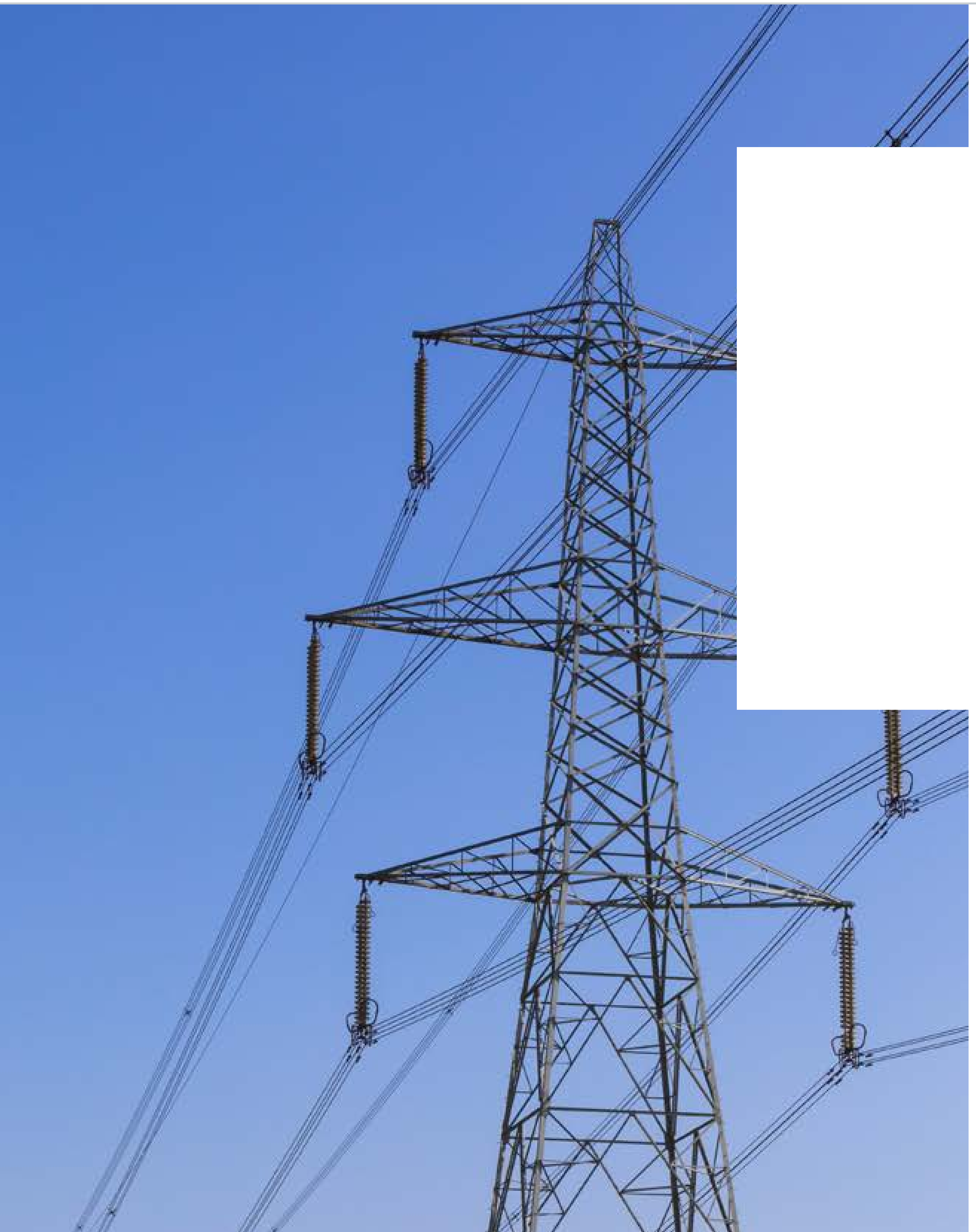
- → Energy Units and Conversion Factors
- → Data Collection and Validation
- → Methodological Notes
- → Glossary
- → List of Abbreviations

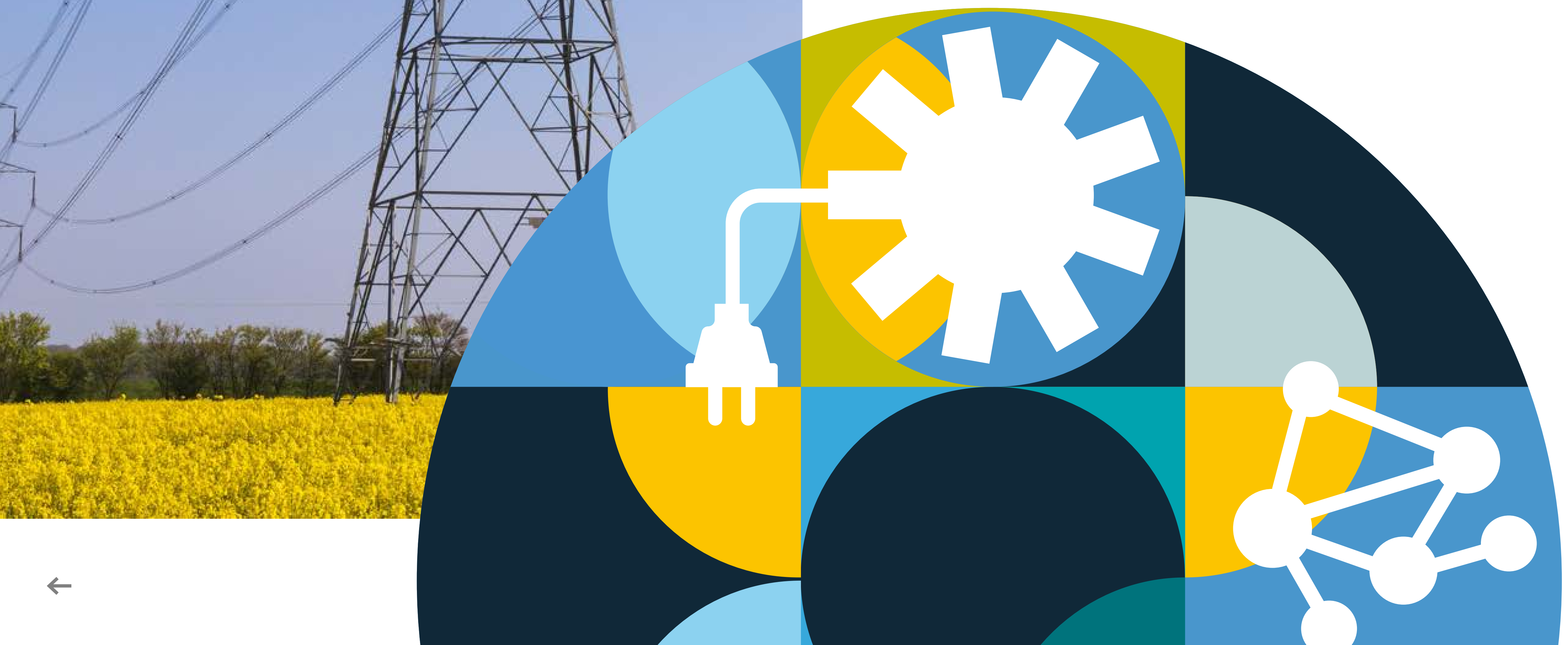
Reference Tables can be accessed through the GSR 2024 *Energy Systems & Infrastructure* Data Pack at

→ http://www.ren21.net/gsr2024-data-pack/systems



MODULE OVERVIEW

This module explores the status and recent trends of some of the building blocks of the energy system, as well as technology advancements that are enabling the integration of higher shares of variable renewable electricity.



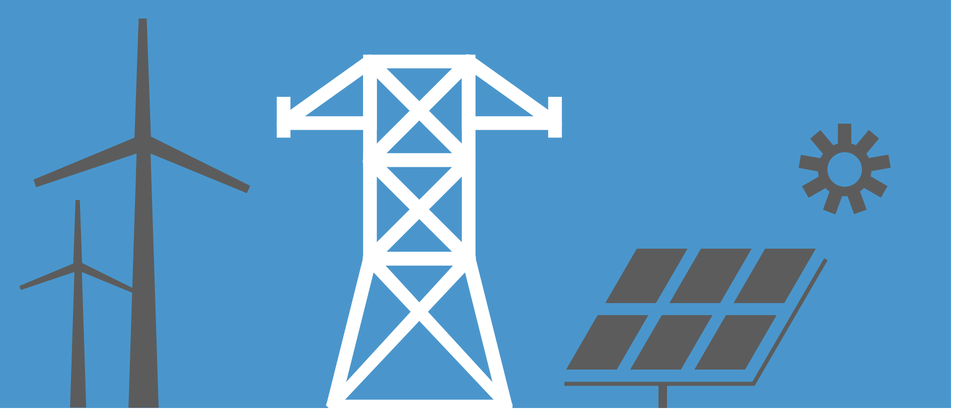
13% share of global electricity from variable renewables (wind and solar power)

1.5 TW renewable power projects in advanced stages of development or under review awaiting grid connection as of end-2022

159% maximum daily penetration of variable renewables in Denmark's electricity system

KEY FACTS

- Global electricity demand increased 27% between 2013 and 2023, putting pressure on existing power grids. In many locations, distributed generation is growing faster than grid capacity.
- Utility-scale battery storage grew 120% in 2023.
- Pumped storage remains the most common solution for large-scale utility storage.
- Investment in hydrogen increased 203% in 2023 to reach USD 10.4 billion. The bulk of hydrogen production worldwide continues to come from fossil fuel sources.



Deployment of renewable energy technologies has increased sharply in the past two decades – particularly in the power sector, driven by the rapid expansion of solar photovoltaics (PV) and wind power.[1] The share of variable renewable energy (wind and solar) in power systems globally exceeded 13% in 2023, with much higher shares (up to 67%) in some countries.[2] (→ *See Box 1.*) As deployment grows, integrating variable energy sources to achieve high shares in utility grids remains a major challenge.

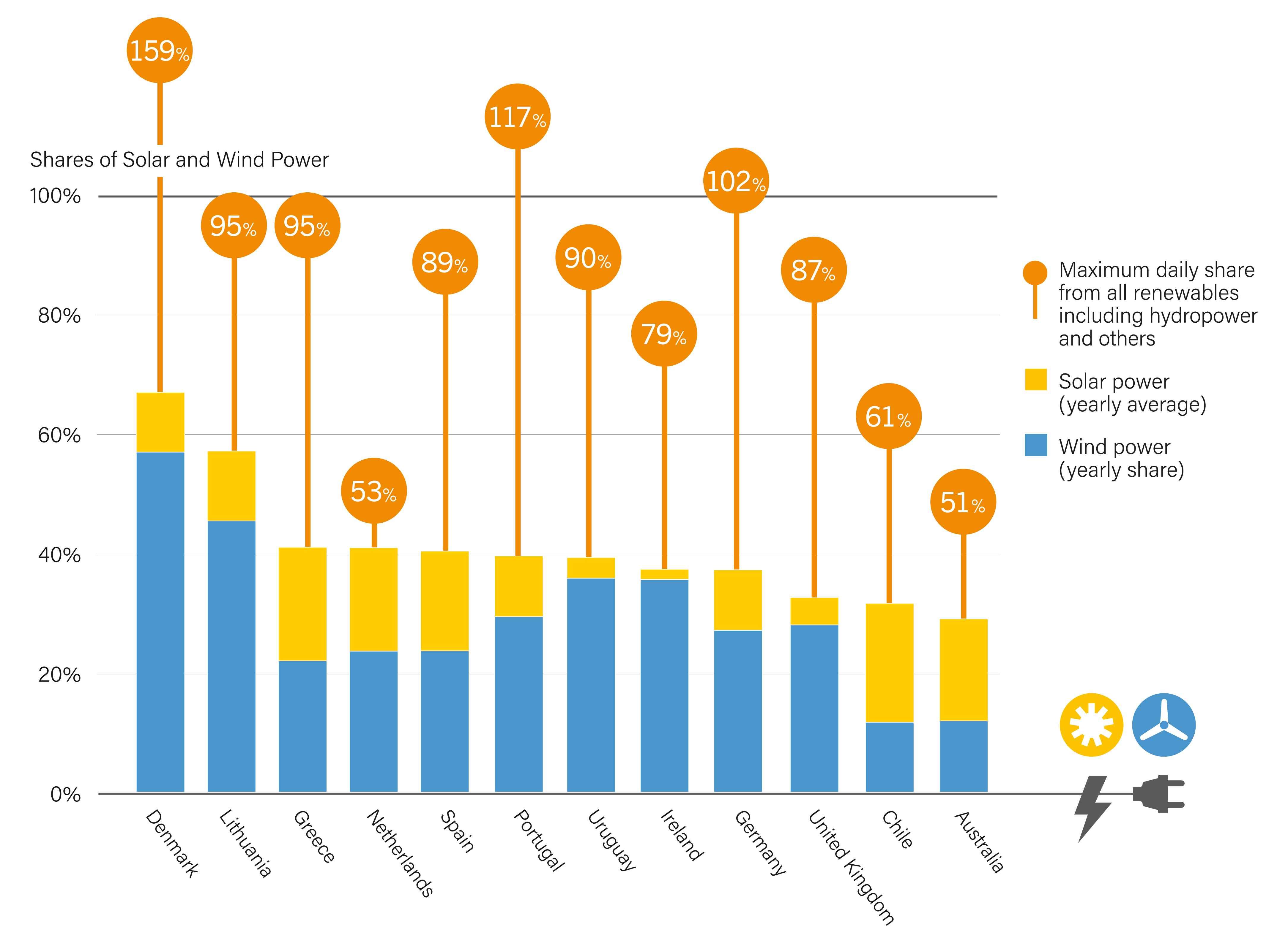
Existing transmission and distribution systems were developed alongside traditional centralised power generation facilities. This allowed for high shares of large-scale, baseload energy generation (such as coal and nuclear power) while also including flexible generation sources (such as fossil gas and hydropower). Much more flexibility is needed to incorporate increasingly decentralised and variable renewable power resources, and to enable demand-side management.[3] Moreover, the overall growth in electricity demand[i] – up 27% globally between 2013 and 2023 – is putting pressure on existing power grids: in many locations, distributed generation is growing faster than grid capacity.[4]

Through integrated energy planning, countries and jurisdictions can assess the status of their energy systems, set objectives such as targets for decarbonisation and the deployment of renewables, and plan for the infrastructure needed to reach these goals.[5] Holistic energy planning includes all energy sectors, beyond power. Heat generation from renewable sources such as

BOX 1. Countries with High Shares of Variable Renewable Power Generation

In 2023, several countries successfully relied on high shares of variable renewable power generation. Denmark led with 67% of its gross electricity from variable renewables (57% wind, 10% solar), and five other countries achieved shares above 40%: Lithuania (46% wind, 12% solar), Greece (22% wind, 19% solar), the Netherlands (24% wind, 17% solar), Spain (24% wind, 17% solar) and Portugal (29% wind, 10% solar). Uruguay (36% wind, 3% solar), Chile (12% wind, 19% solar) and Australia (12% wind, 17% solar) also have incorporated high shares of variable generation. (→ *See Figure 1.*)

FIGURE 1.
Top Countries for Share of Variable Renewable Electricity Generation, and Maximum Daily Penetration, 2023



Note: The figure shows the countries with the highest shares according to the best available data at the time of publication. Several smaller countries with low total generation are excluded from this list. For Chile and Uruguay, the maximum daily share is replaced by the average yearly renewable electricty share, as data were not available at the time of publication.

Source: See endnote 2 for this module.

[i] Key factors contributing to the rapid growth in electricity demand include: the ongoing electrification of end-use sectors (residential, transport and industry), improving economic outputs in both advanced and emerging economies, expansion of data centres and the increased demand for cooling in the face of extreme heat.

geothermal, solar thermal, bioenergy, and waste heat can be integrated into the overall design of energy systems.[6] (→ *See Snapshot: Europe*). In the transport sector, an integrated approach can be taken through the use of renewable fuels, electrification, and a focus on demand reduction through active mobility (cycling and walking) and public transport. Integrated energy planning can reduce electricity demand, increase renewable energy uptake and alleviate pressure on power grids.[7]

Power system planning can include assessments of flexibility needs and integration across energy market segments (for example, considering developments in both generation and transmission), as well as across energy demand sectors that are rapidly electrifying, such as transport and buildings.[8]

Power networks carry all sources of electricity, regardless of the generation technology. However, optimising these networks makes it possible to effectively integrate higher shares of variable renewable energy, while coping with increased electricity generation and consumption. This requires optimising or expanding the existing transmission and distribution infrastructure, implementing forecasting methods and demand response measures (often through the use of digital technologies), using energy storage, and coupling electricity generation with other sectors.[9]

This module explores the status and recent trends of some of the building blocks of the energy system, as well as technology advancements that are enabling the integration of higher shares of variable renewable electricity.

Grids are the backbone of the electricity system, allowing power loads to flow from generation centres to points of consumption. **Grid congestion** occurs when the grid capacity is not sufficient to transport the power loads.[10] In many places around the world, the installed capacity of renewable power has grown faster than the network capacity. By the end of 2022, 1.5 terawatts of renewable power projects in advanced stages of development or under review globally were awaiting connection to grids.[11] The amount of renewable power generation that was **"dispatched down"**[i] because of curtailment and system constraints also increased in 2023.[12]

During the year, several countries and regions – including Argentina, Belgium, Brazil, Canada, the European Union (EU), India, Japan, the Netherlands, South Africa and the United States – announced significant investments and reforms to enhance their **electricity grids**.[13] Global investment in power grid infrastructure reached USD 310.2 billion in 2023, led by investments in the United States and China.[14]

Regional interconnections and market integration are crucial for grid reliability, flexibility and security of supply.[15] Ongoing interconnection projects in 2023 included the Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP), the Celtic Interconnector between France and Ireland, the Italy-Greece sub-sea cable in Europe, the Egypt-Saudi Arabia electricity link in the Middle East and North Africa region, the Zimbabwe, Zambia, Botswana, Namibia (ZiZaBoNa) and the Zambia-Tanzania-Kenya (ZTK) interconnectors in Africa, the Andean Electrical Interconnection System (SINEA) and the Regional Energy Integration of the Southern Cone (SIESUR) in South America and several transmission line projects in the United States.[16]

Grid optimisation
and expansion attracted growing policy attention and investment in 2023.

Digitalisation for grid flexibility and optimisation – including the use of virtual power plants (VPPs) and grid-enhancing technologies – continued to attract policy and market attention during the year.[17] Together with the roll-out of smart meters to manage **demand-side flexibility**, these technologies have been deemed effective for integrating growing shares of renewables and ensuring stable and efficient grid operation.[18] Several policies also emerged in 2023 to promote the development of microgrids.[19]

Utility-scale **battery storage** grew 120% in 2023 to reach 55.7 gigawatts (GW) globally.[20] The growth was led by China, the United States, the United Kingdom, Germany, and Ireland, while Australia, the Republic of Korea and Japan also remained important markets in 2023.[21]

The world added 6.48 GW of **pumped storage** capacity in 2023 – down 38% from the previous year's additions – for a global total of 179 GW.[22] Pumped storage remains the most common solution for large-scale utility storage, being cost-effective in many regions.[23]

Sector coupling facilitates higher shares of renewables by providing the system flexibility required by variable renewables – for example, by linking the power sector with the heating and cooling sector (to meet thermal needs) and with the transport sector (to charge electric vehicles). Other applications, such as power-to-hydrogen transformations, also are being explored.[24]

Renewable hydrogen continued to attract attention in 2023, with 7 countries announcing or revising their hydrogen strategies or roadmaps, bringing the total number of countries with strategies or roadmaps to 55.[25] Investment in renewable hydrogen increased 203% to reach USD 10.4 billion (of which 84% was for electrolysers).[26]

The expansion of **electric vehicle (EV) charging infrastructure** is essential to support the growing electrification of the transport sector. However, it introduces new constraints and opportunities to consider in power network optimisation, such as increased uncertainty around power demand and load times, but also increased flexibility through targeted charging hours and bi-directional charging.[27] As of 2023, 20 jurisdictions (including the EU) had regulatory and fiscal and financial policies for EV charging infrastructure, up from 14 jurisdictions in 2022; meanwhile, 8 new jurisdictions introduced targets for the deployment of EV charging infrastructure, for a total of 33 jurisdictions having such targets.[28]

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[i] Dispatch down occurs when the transmission system operator instructs a renewable power generator to produce less electricity than it is able to, or even to stop generation entirely.

SNAPSHOT EUROPE

HARNESSING WASTE HEAT FROM DATA CENTRES

In 2022, data centres worldwide consumed around 460 terawatt-hours (TWh) of electricity – equivalent to 2% of the global total and more than the annual electricity consumption of France. In Ireland, data centres used 20% of the country's electricity supply in 2023, and this share could reach 70% by 2030. Around 40% of a data centre's total energy use is for cooling, and excess heat is released into the atmosphere through cooling towers or evaporative condensers, literally throwing this heat away.

Many data centres are installing renewables such as wind and solar power to power their facilities. However, finding ways to optimise and store large amounts of produced energy is key. Across Europe, many examples of recycling the heat from data centres have emerged. In 2010, the Finnish information technology company Academica installed a 2 megawatt (MW) data centre in the caves beneath Helsinki's Orthodox Uspenski Cathedral. In the Gronigen region of the Netherlands, a large data centre is connected to the district heating grid. Similarly, in Tallaght, Ireland, a district heating network was built to harness waste heat from an Amazon data centre to supply hot water. Waste heat from data centres is being used to heat sea water at a land-based lobster farm In Norway, to grow algae on-site in Germany and to supply the heat network of a hospital in Austria.

In the UK, a public swimming pool is heated by an on-site data centre, and up to 150 public swimming pools are exploring ways to recycle excess heat. In Scotland, the University of Edinburgh is recovering heat from its data centres to supply university buildings.

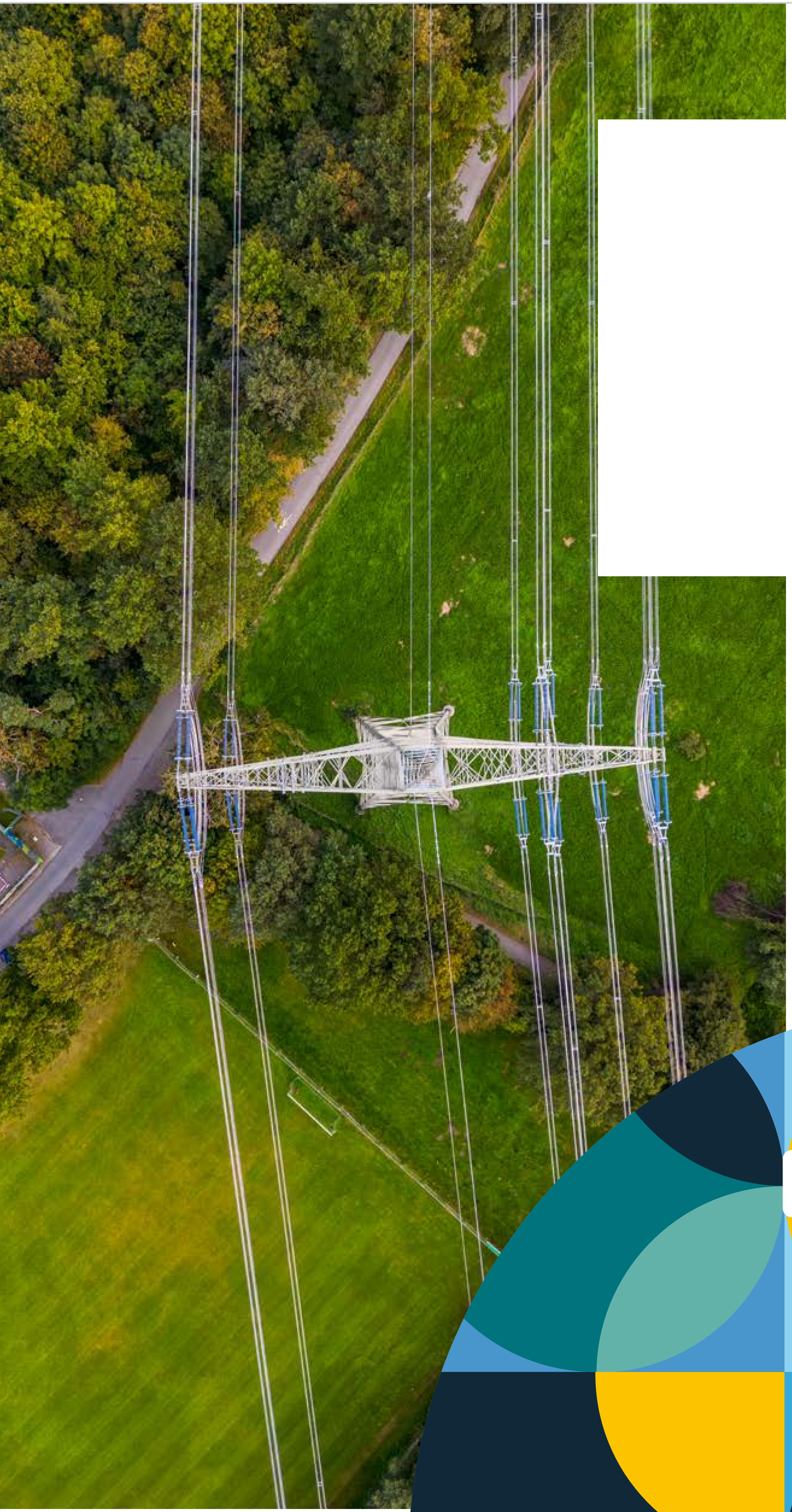
Challenges remain to scale such applications, as large data centres are often located in industrial zones outside of residential areas, potentially far from customers who might want to utilise the heat. Furthermore, to be useful for certain applications, the low-temperature heat that most data centres produce must be compressed into higher-grade heat, a process that can be prohibitively expensive. In some places, the waste heat from heavy industries such as smelting or incineration facilities is better suited for the district heating market.

Source: See endnote 6 for this module.

Data centres consumed

2%

of the global electricity demand in 2022.



ELECTRICITY GRIDS

In 2023, power grids received increased attention from policy makers and investors to keep pace with surging renewable power generation and the rising number of interconnection requests.

310 **billion USD** global investment in grids in 2023

5% increase in grid investment in 2023

KEY FACTS

- Most of the grid investment in 2023 was in the United States (USD 86.5 billion, or 27.9%) and China (USD 78.9 billion, or 25.4%), followed by Germany, Canada and India.
- In most emerging and developing countries, investment in electricity networks was hindered due to financial and affordability constraints.

In 2023, the world's power networks struggled to keep pace with the surging deployment of renewables and with increasing requests for grid connection. Queues of projects under development continued to grow. During the year, an estimated 1,500 GW of renewable energy projects in the late stages of development or under review were awaiting grid connection, and this figure doubles to an estimated 3,000 GW when projects in the earlier stages of development are also considered.[29]

In Viet Nam, the recent growth in solar PV capacity was not supported by adequate capacity in the country's transmission network. As a consequence, further PV capacity additions are expected to be limited to around 2.4 GW to 2030.[30] In the United States, due to connection procedures, it typically takes a project five years from the interconnection request to reach commercial operations.[31] Distribution networks also face challenges, including in Germany and the Netherlands, where networks are highly congested.[32]

In advanced economies such as in Europe or the United States, the planning, permitting and implementation of high-voltage and extra-high-voltage overhead lines at the transmission and sub-transmission level can take 10 years or more.[33] This is much longer than the typical periods required for implementing renewable generation facilities. Other factors contributing to long timelines for grid expansion projects are a lack of integrated planning, regulatory frameworks and funding; supply chain delays and technical difficulties; long permitting procedures and administrative understaffing; and stakeholder opposition.[34] In developing economies, access to finance and the high cost of capital remain key barriers.[35]

In 2023, the **EU** presented an electricity market reform that proposes a two-way Contract for Difference[i] mechanism for all new investment in low-carbon[ii] electricity production[iii],[36] Within the market design reform, EU Member States are required to assess their needs for power system flexibility – such as demand response and storage to support the integration of non-fossil energy sources – and to define objectives to this aim.[37] The European Commission also presented a 14-point Action Plan for Grids that aims to address structural issues, enhance grid infrastructure, support supply chain standardisation for grids, reduce lengthy connection queues, and attract the estimated USD 636 billion (EUR 584 billion) required in grid investment to reach the region's decarbonisation targets.[38]

The Netherlands developed a National Grid Congestion Action Programme that aims to speed investment and reduce connection queues through grid expansion and increased flexibility.[39] In **Belgium**, a construction permit was issued for the first artificial energy island (Princess Elisabeth Island), which will act as a central energy hub using high-voltage current technologies to connect offshore wind farms with the mainland grid and eventually with power networks in neighbouring countries.[40]

In the **United States**, the Department of Energy announced the Grid Resilience and Innovation Partnerships (GRIP) programme, which has awarded projects related to smart grid updates, adaptive networked microgrids, battery storage, flood mitigation of sub-stations, network capacity upgrades, and the hardening of existing transmission lines to increase their resilience to extreme weather events (focusing on disadvantaged communities).[41] **Canada**, in its 2023 budget, allocated USD 2.2 billion (CAD 3 billion) over a 13-year period to recapitalise funding for the Smart Renewables and Electrification Pathways Program.[42] In South America, **Argentina** approved a plan to expand the high-voltage electricity transmission system, and **Brazil** conducted auctions for the expansion of around 4,500 kilometres of power transmission.[43]

Under its Green Energy Corridor scheme, **India** approved the construction of an inter-state transmission system to evacuate the 13 GW of capacity generated at a large-scale renewable energy project in Ladakh.[44] **Japan** developed an expansion plan in early 2024 to connect the capital city of Tokyo to the northern island of Hokkaido, as well as to increase the transmission capacity between the western regions of Kyushu and Chugoku 30% by 2030.[45] In 2023, **South Africa** reviewed its Integrated Resource Plan, which prioritises further development of the transmission grid, among other measures.[46]

Global **investment** in power grid infrastructure[iv] increased 5.3% in 2023 to reach an estimated USD 310 billion.[47] Most of this investment was in the **United States** (USD 86.5 billion, or 27.9%) and China (USD 78.9 billion, or 25.4%), followed by **Germany**, **Canada** and **India**.[48] (→ *See Figure 2*.) In most emerging and developing countries, in contrast, investment in electricity networks was hindered due to financial and affordability constraints.[49]

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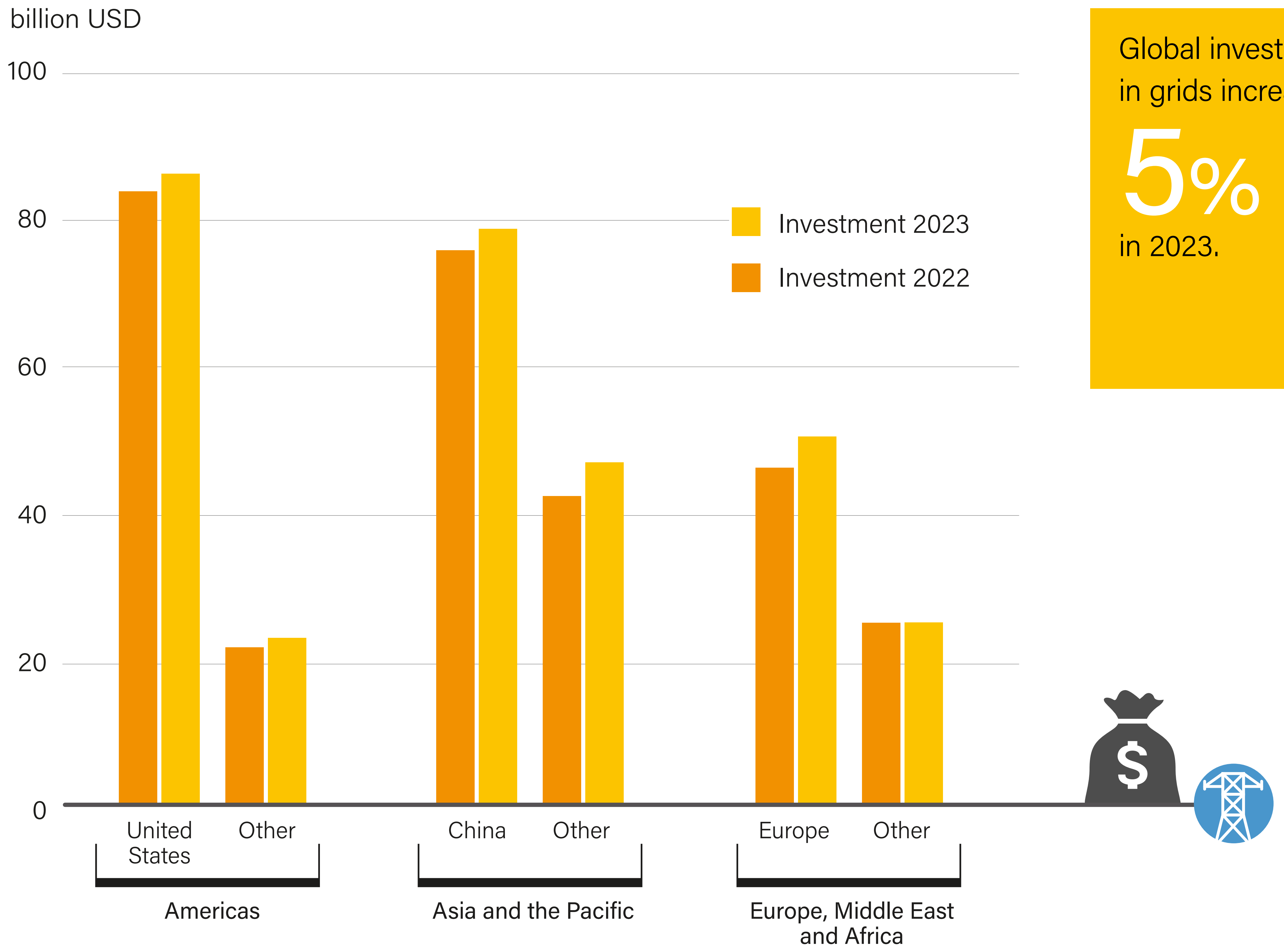
[i] This mechanism aims at creating a buffer between electricity markets that are heavily dependent on global fossil fuel prices, and consumer bills. Producers of renewable energy (excluding hydropower with reservoirs) receive payments if market prices fall below a certain level and pay back when prices exceed a certain level, ensuring revenue stability and encouraging investment in renewables. The reform was approved in May 2024.

[ii] This includes wind, solar, geothermal, and hydro power (without reservoir) as well as nuclear energy.

[iii] The proposal was approved in 2024.

[iv] Data from BloombergNEF do not include a breakdown of grid infrastructure. It is assumed that this includes transmission and distribution grids.

FIGURE 2.
Investment in Electricity Grid Infrastructure by Major Country/Region, 2022 and 2023



Global investment in grids increased
5%
in 2023.

Source: See endnote 48 for this module.

In the United States, the focus has been mainly on enhancing reliability and upgrading outdated infrastructure, with the GRIP programme receiving USD 3.9 billion in funding for grid modernisation.[50] In 2023, the budget of the US Department of Agriculture allocated USD 300 million to help rural electricity providers shift to clean energy, including through transmission updates and energy storage expansion.[51] California's independent system operator (CAISO) approved a USD 7.3 billion plan to build new high-voltage transmission lines.[52]

In China, grid investments continued to grow, particularly for ultra-high voltage transmission projects but also for upgrading the distribution network and digitalising grids.[53] In Europe, investment was focused on connecting offshore wind farms, modernising ageing infrastructure, and digitalising grids to allow for demand-side load management, EV charging and electrification of industry.[54] Latvia allocated USD 53 million (EUR 49 million) towards modernising the electricity distribution grid by 2026 through a partnership with the Latvia Electricity Distribution Company.[55] Australia included in its 2022/2023 budget a USD 13.6 billion (AUD 20 billion) grant for upgrading and expanding the grid via the Rewiring the Nation Fund.[56]

Countries worldwide have focused on permitting processes to better respond to changing electricity generation patterns and to ease the connection queues affecting renewable energy projects. The EU's New Renewable Energy Directive, adopted in 2023, offers Member States the possibility to designate and develop "grid acceleration areas" – areas with high renewable energy potential and low environmental impacts – where permitting times would be reduced.[57] In the United Kingdom, the transmission system operator announced reforms to improve the connection queue backlog.[58]

In the United States, the government has outlined faster permitting as a priority.[59] The programme Renewable Energy Siting through Technical Engagement and Planning (R-STEP) aims to enhance the decision-making capacity and expertise of state and local governments around large-scale renewable energy planning, siting and permitting.[60] The new interconnection rules issued by the US Federal Energy Regulatory Commission aim to reduce backlogs for projects to connect to the transmission system.[61]

Other environmental aspects to consider in the optimisation of power grids include the materials and substances used, such as insulating gases.[62] (→ *See Sidebar 1.*)

SIDEBAR 1. Reducing the Use of SF_6 Gas to Improve the Climate Footprint of Power Grids

Power networks do not consist only of overhead lines and underground cables. Each connection in a transmission and distribution network includes switchgear, or metal-enclosed components such as switches and circuit breakers that conduct or interrupt the flow of electrical currents. For decades, switchgear has used sulphur hexafluoride (SF_6) as an insulating gas. While SF_6 allows for the compact and cost-effective design of electrical assets, it is also the most potent greenhouse gas ever used on an industrial scale, with a global warming potential 25,200 times that of carbon dioxide. As atmospheric concentrations of SF_6 began to surge in the last century, the gas was targeted under the 1997 Kyoto Protocol and has since been banned and replaced in many applications. However, electrical switchgear has remained one of the few tolerated uses and is now among the major sources of SF_6 emissions.

Although substantial progress has been achieved in monitoring, reducing and managing leakages of SF_6 from network assets, leakages cannot be avoided completely. A complicating factor is that network assets have a long nominal life of 35 to 40 years and may remain in operation for 60 years or more. Because emissions are likely to occur during this period, policy initiatives aimed at replacing SF_6 have been pursued for more than a decade.

Recently, in parts of the United States and Europe, such announcements have been translated to legally binding provisions prohibiting the use of SF_6 in new installations. The restrictions apply depending on voltage and current ratings: for medium-voltage switchgear, they apply starting in 2025 in California and 2026 in the EU, and for all voltage and current ratings, they apply starting in 2032 (EU) and 2033 (California).

In 2023, the G7 countries announced their commitment to phase out the use of SF_6 in new switchgear applications by 2024. Other countries (such as China and the Republic of Korea) also have implemented regulations to incrementally replace SF_6 with alternatives in new equipment.

As manufacturers have anticipated these changes, they have introduced alternatives or announced their discontinuation of SF_6 use. A growing range of SF_6-free solutions is commercially available or in the prototyping stage. Manufacturers have an interest in scaling up production of new designs and, in the longer term, supporting design convergence to avoid parallel investment in different technologies. This may also affect markets that do not have legally binding restrictions.

The transition away from SF_6 presents an added challenge for network expansion, as the gas has long been the de facto standard. In adopting alternatives, companies must make strategic choices with consequences far beyond 2050. Many companies are reluctant to shift because the supply chain remains limited, and there is little long-term operational experience with SF_6-free solutions. Initial investments in alternatives may be higher, and new design constraints may apply. Nevertheless, if the network industry wishes to take climate targets seriously, it must move away from SF_6. in the EU, manufacturers and project developers of renewable generation technologies (such as wind energy converters or large solar PV plants) are immediately affected by the new regulations. Because these products and projects depend on the use of medium-voltage switchgear, SF_6-free alternatives need to be applied in current designs.

Source: See endnote 62 for this module.

DISPATCH DOWN OF RENEWABLES

At the operational stage, renewable energy projects are affected by system constraints. In many countries, generation from variable renewables (wind and solar power) has increasingly been dispatched down – reduced or suspended at the request of system operators – to cope with system limitations.[63] (→ *See Box 2.*) While some level of temporary curtailment of renewables can be expected in a system that incorporates higher shares of variable generation, minimising the associated yield losses is a key objective of system optimisation.[64]

If the dispatch down of renewables occurs at times of high demand, the consequences can be significant. During a heat wave in **Viet Nam** in 2023, network congestion resulted in only 10.5 GW of the country's 20 GW of solar capacity being used on average at peak times.[65] In **Japan**, curtailment reached a record high of 1.76 TWh between April 2023 and March 2024.[66] In **Germany**, curtailment measures reportedly led to an estimated loss of 19 TWh of electricity in 2023, up from 8 TWh in 2022.[67]

BOX 2. Reasons for the Dispatch Down of Renewables

Dispatch down is the action of reducing or stopping energy generation in response to an instruction from the system operator. The reasons for such requests can be **curtailment** and **constraints**, and they relate to different limiting mechanisms.

Constraints are caused by insufficient transport capacity, resulting in network congestion. This may apply to distribution, sub-transmission or transmission networks. Weak sections of local networks may require constraints even at low overall penetration of variable renewable energy. These weak spots indicate a potential need for network optimisation. Additionally, significant shares of variable renewable capacity are connected to distribution and sub-transmission networks. This distributed generation is collected at the transmission level, and hence congestion may occur here.

Technologies that allow for dynamic adjustment of line ratings depending on climate conditions help to relax network limitations. During the last decade, those technologies became mature and have been applied successfully in various countries.

Curtailment is related to diverse operational limits of the power system. These limits may depend on the type of power generation facilities that compose the system (e.g., wind, solar, hydropower, coal) and how their technical characteristics can be used to maintain the stability of the system, considering factors such as frequency and voltage control. Such limits become relevant only at high levels of penetration of instantaneous non-synchronous electricity sources. So far, they are of minor relevance in large and interconnected power systems but more relevant for electrical islands. Reported dispatch down of renewables is mostly related to network congestion.

Generation from conventional power plants typically sets an upper limit to generation of variable renewable energy. These plants provide necessary ancillary system services on top of their electricity output. Experience shows that solar and wind power plants can provide ancillary services, for example using grid-forming converters and battery storage. With technology becoming mature and standardised, these barriers for the integration of renewables can be overcome.

Source: See endnote 63 for this module.

REGIONAL INTERCONNECTIONS

Regional interconnections and market integration can help improve the reliability and security of grids and the quality of supply, while also enabling greater integration of renewable energy and demand-side resources. Sharing surplus power generation and balancing electricity supply and demand across regions can reduce the impact of disruptions and enable the efficient use of resources, supporting a more flexible and robust energy system.[68]

Among positive developments in 2023, in **South-East Asia** the Lao PDR, Thailand, Malaysia and Singapore Power Integration Project (LTMS-PIP) was signed during a side event at the 41st ASEAN Ministry of Energy Meeting in August 2023, along with a memorandum of understanding for 18 potential locations where cross-border transmission lines could be set up.[69] (→ *See Snapshot: South-East Asia.*) **India**, co-leader of the One-Sun-One-World-One-Grid initiative, also started discussions to increase its cross-border interconnections with the Maldives, Saudi Arabia, Singapore, Sri Lanka and the United Arab Emirates.[70]

In Europe[i], the Celtic Interconnector project – a 575 kilometre sub-sea interconnector developed by the transmission system operators of France (RTE) and Ireland (EirGrid) – started construction in 2023 and will enable the transmission of 700 MW of power between the two countries.[71] A project for a 250 kilometre sub-sea cable and 1 GW of connection capacity was also approved to increase interconnection between **Italy** and **Greece**.[72] Additionally, the EU Connecting Europe Facility (CEF) allocated a grant of USD 331 million (EUR 300 million) to construct a power cable between **Italy** and **Tunisia**.[73]

Regional interconnections help **stabilise power networks** and enable higher shares of renewables.

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[i] In 2018, the EU set a target for 15% electric interconnectivity by 2030, which is reflected in the National Energy and Climate Plans of EU Member States. See endnote 71 for this module.

SNAPSHOT SOUTH-EAST ASIA

HARNESSING CROSS-BORDER SYNERGIES: THE LAO PDR-THAILAND-MALAYSIA-SINGAPORE POWER INTEGRATION PROJECT AND THE ASEAN POWER GRID INITIATIVE

The ASEAN Power Grid (APG) initiative is working to integrate the power systems of South-East Asian countries through cross-border energy interconnections and harmonised rules. Identified as an area of co-operation for the Association of Southeast Asian Nations (ASEAN) in 1999, the APG seeks to create an integrated regional electricity grid.

The Lao PDR-Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP), which began operations in 2022, is the first multilateral cross-border electricity trading initiative in the region and serves as a key step towards regional energy co-operation and integration under the APG. This project facilitates the transfer of electricity, via existing infrastructure, from Lao People's Democratic Republic (PDR) to Singapore through Thailand and Malaysia, thereby demonstrating the feasibility of multilateral power trade in the region.

The primary objectives of the LTMS-PIP include enhancing regional energy security and economic efficiency by sharing renewable energy resources across borders, particularly drawing on the abundant hydroelectric capacity of Lao PDR (8,108 MW as of 2023). The initiative will help participating countries meet their climate and sustainability goals by supporting the transition to renewable energy sources. It also creates a blueprint for future multilateral energy trading projects to promote the development of a regional energy market.

Through the LTMS-PIP, Singapore will import up to 100 MW of electricity from Lao PDR. The current agreement runs through the end of 2024, with potential plans to extend it by another three years and to increase imports to 300 MW. Singapore has limited opportunities for domestic renewable energy production due to its small land area; however, the country has ambitious renewable energy targets and plans to import 4 GW of low-carbon electricity[i] by 2035. Energy imports through partnerships such as the LTMS-PIP will assist Singapore in overcoming its geographical constraints and achieving its targets. The country is also exploring other similar agreements; for example, it plans to import 1.2 GW of wind power from Viet Nam via a sub-sea cable.

In April 2023, construction began on a 600 MW onshore wind energy project in southern Lao PDR. The project is funded by the Asian Development Bank and the Japan International Cooperation Agency and is led by Monsoon Wind Power, a consortium that includes Mitsubishi and ACEN Renewables International, among other companies.

It is the country's first wind farm and will be the largest in South-East Asia. Lao PDR plans to export a portion of the wind farm's generated power through a 65 kilometre, 500 kilovolt (kV) transmission line as part of a 25-year agreement signed with Vietnam Electricity. The project aims to be in operation by 2025 and signifies further potential for cross-border power generation and trade.

Cross-border energy interconnections such as these highlight how space limitations and renewable resource constraints do not need to impede progress towards a global energy transition. They also highlight the importance of effective governance mechanisms and collaboration from participating countries in managing the complexities of multilateral projects.

Source: See endnote 69 for this module.

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[i] Low-carbon electricity includes renewable energy as well as nuclear power, fossil fuels with carbon capture, utilisation and storage (CCUS), hydrogen and ammonia.

An interconnector linking the electricity networks of **Egypt** and **Saudi Arabia** by 2025 started its testing phase in 2023. The project is expected to support the exchange of 3 GW of power between the two countries and involves the installation of 1,350 kilometres of sub-sea cables across the Red Sea.[74]

In **Africa**, interconnection projects in the feasibility or development stages include the ZiZaBoNa interconnector, which was initiated in 2008 and will link the electricity networks of Zimbabwe, Zambia, Botswana and Namibia; in 2023, the project secured partial funding from the African Development Bank.[75] Additional projects in the region include the Zambia-Tanzania-Kenya (ZTK) Interconnector, which is expected to link the Southern Africa Power Pool (SAPP) to the Eastern Africa Power Pool (EAPP), and the MoMa interconnector between Mozambique and Malawi.[76]

In **South America**, two of the four main regional interconnection projects made advances in 2023. A 2020-2030 roadmap was signed to advance the development of the Andean Electrical Interconnection System (SINEA), a project started in 2011 and supported by the Inter-American Development Bank that aims to enable electricity exchanges between Bolivia, Chile, Colombia, Ecuador and Peru.[77] In addition, the roadmap for the Regional Energy Integration of the Southern Cone (SIESUR) initiative – aimed at creating a market for electricity exchanges between Argentina, Brazil, Chile, Paraguay and Uruguay – was updated for 2023-2032, focusing on the analysis of regulatory and technical frameworks and currency exchange risk assessment.[78]

In the **United States**, the Department of Energy committed USD 1.3 billion to three transmission line projects – the Cross-Tie 500 kV Transmission Line (Nevada and Utah), the Southline Transmission Project (Arizona and New Mexico) and the Twin States Clean Energy Link (New Hampshire and Vermont) – which together will increase the national grid capacity by 3.5 GW.[79] Additionally, the DOE released the National Transmission Needs Study and the Transmission Interconnection Roadmap aimed at strategically enhancing transmission infrastructure to support clean energy integration across the country.[80]

Developing large-scale interconnections involves not only significant funding, but also technical capacity and the alignment of regulatory frameworks and markets. To provide guidance on these complex processes, the Green Grids Initiative released draft Principles for Interconnectors, providing step-by-step guidance to countries for the development of interconnectors.[81]

GRID-ENHANCING TECHNOLOGIES

Research and industry have increasingly focused on digitally driven solutions to optimise and increase the capacity of existing power lines.

The maximum loads of power lines are traditionally defined by a static conservative upper limit to prevent overheating. **Dynamic line rating** (DLR) makes it possible to optimise the loads of power lines by adjusting their availability to their exact capacity at a specific time, considering real-time weather conditions. DLR enables the grid to operate closer to its maximum capacity for longer periods, thus increasing the average load and potentially allowing the avoidance or postponement of network extensions (although it does not increase the absolute line rating).[82] As of 2023, DLR technology had been deployed – or was in the testing phase – in more than 25 countries, following the research and development stages of the 1990s and the installation of the first pilot projects in the 2000s.[83]

DLR technology had been deployed or was in the testing phase in more than
25 countries
as of 2023.

Advanced power flow control technologies can balance the flow on transmission lines by allowing lines with spare capacity to pull more power and thus reduce constraints on overloaded lines. This increases the total current delivered by re-routing the power in real time, thereby enhancing the grid's overall power transfer capacity.[84] As of 2023, at least 10 countries were reportedly using or testing advanced power flow control technology, including Australia, Colombia, Ireland, France, Greece, the United Kingdom and the United States; in the United States, two projects awarded under the GRIP programme aim to improve flexibility and increase transfer capacity for renewable energy generation.[85]

Topology optimisation software identifies reconfigurations of the transmission system that can alleviate constraints by re-routing power flow around these constraints.[86] Whereas advanced power flow control actively manages the real-time distribution of power, topology optimisation focuses on strategically adjusting the configuration of the transmission network. As of 2023, projects were ongoing in the United Kingdom and the United States.[87]

Research on grid-enhancing technologies suggests that these solutions can be much cheaper and easier to implement than the network upgrades that they replace.[88] Existing commercial projects in Europe and the United Kingdom, as well as evaluations from the United States, suggest that these technologies can increase grid capacity from a small percentage (for small grid applications) to up to 100% in the case of complex grids with multiple possible routes.[89]

DEMAND FLEXIBILITY AND TIME-VARIANT NETWORK CHARGES

In many parts of the world, power loads in the residential and commercial sectors have grown rapidly. Markets for new loads – such as electric vehicle charging and heat pumps – are ramping up and are expected to grow further in the coming decade. Congestion in (low-voltage) distribution networks is therefore increasingly a concern. As with transmission, network extension and reinforcement need to be combined with approaches that allow for efficient use of the existing infrastructure.[90]

In liberalised power markets that have high shares of variable renewable energy, (sub-)hourly electricity prices fluctuate greatly because of the dynamic nature of the residual load and the varying cost structure of the supply. Initial steps have been taken to incentivise load flexibility by translating spot electricity prices to time-varying end-user tariffs.[91] However, a large portion of end-user tariffs are network charges, and, so far, these are not time variant. At the transmission level, extensive experience exists with location-dependent network charges for generators.[92] At the distribution level, network charges for end-users have always been fixed.

Addressing these issues entails several challenges. Historically, low-voltage distribution networks have lacked extensive monitoring and control facilities, making it difficult to assess the actual operational state of network assets.[93]

In **Germany**, the network regulator Bundesnetzagentur has required the industry to propose methodologies for state estimation in distribution networks to improve grid management and efficiency.[94] These methodologies must be immediately applicable, without the need for extensive SCADA infrastructure, to facilitate quicker implementation. The goal is to introduce time-variable network charges by 2028, allowing the distribution system operator to better control loads, reduce congestion, and enhance overall grid reliability and efficiency.[95]

Various countries have implemented programmes to manage and optimise electricity consumption, building on long-established **demand-side management** (DSM) practices. DSM involves methods to reduce or shift electricity use during peak periods, enhancing grid stability and achieving energy savings. Governments and regulators have long used DSM to reduce peak demand from energy-intensive operations, particularly in industry.[96] At the residential level, modern demand flexibility services leverage advanced technologies to expand these benefits. These initiatives showcase how demand flexibility can effectively reduce peak demand, enhance grid stability and provide significant energy savings.[97]

Through a demand flexibility programme in the **United Kingdom**, launched in the winter of 2022/23, 1.6 million domestic and non-domestic customers were remunerated for shifting their demand during peak hours, enabling savings of 3,300 megawatt-hours (MWh) across 22 total events.[98] The programme was relaunched in winter 2023/24, with participation increasing to 2.6 million customers and savings to more than 3,700 MWh.[99] In **France**, where the transmission system operator RTE awards load reduction through capacity auctions, around 2.8 GW of demand reduction was awarded in 2023 (for auctions in 2024), slightly above the volume awarded in 2022.[100]

In December 2022, the **Republic of Korea** launched a pilot programme for Auto Demand Response, enabling intelligent appliances to automatically respond to demand reduction requests, eliminating the need for manual input from consumers and resulting in a 24% improvement in electricity savings.[101] The South Korean Energy Pause Programme – launched in 2018 to target households, small shops and businesses – already incentivises electricity reduction during peak periods through financial rewards and discounts.[102] In **Japan**, where capacity tenders are open to demand response, 2.3 GW of successful bids were achieved in 2022; during severe winter power shortages, demand response contributed 90 GW in the additional supply capacity market.[103]

In **South Australia**, certain types of air conditioners installed from 1 July 2023 must comply with demand response requirements to ensure that they can provide flexibility to the grid; however, consumer participation in demand-side programmes is not mandatory.[104]

Smart metering can increase system flexibility and thereby integration of renewable energy. In 2023, **Germany** adopted legislation to relaunch the roll-out of smart meters throughout the country, after an earlier law from 2019 failed to result in sufficient deployment.[105] In **Australia**, the Energy Market Commission completed a review of the regulatory framework for metering services and was in the process of amending rules to facilitate more efficient roll-out of smart metering technologies.[106] The regulator released a draft determination proposing a mandatory 100% roll-out of smart meters by 2030 and better access to power-quality data from smart meters, while aiming to improve the customer experience and to implement safeguards to protect customers from potential cost risks.[107]

In the **Brazilian** state of Paraná, the power utility Copel announced that it had installed half a million smart meters by the end of 2023 across its operating areas, in the first phase of a project to add 1.6 million smart meters in the coming years.[108] **Uruguay** launched a tender for smart meters to support a plan by the state utility UTE to equip all residential customers with the units by the end of 2024; the company had deployed 1 million units as of 2023 and plans to expand the scheme to small and medium-sized enterprises.[109] **Costa Rica** was awarded concessional funds in 2023 to deploy smart grid projects, including the roll-out of smart meters, aimed at covering two-thirds of the country.[110]

In **India**, the Smart Meter National Programme aims to replace 250 million conventional electricity meters with pre-paid smart meters[i],[111] The roll-out of smart meters enables remote daily meter readings and provides consumers with real-time data, helping them make more informed decisions about their electricity consumption.[112] India also has simplified smart metering rules and reduced penalties for exceeding sanctioned loads.[113] In 2023, the government introduced a time-of-day tariff that incorporates time variability in electricity prices, offering reductions of 10-20% during specified "solar hour" periods of eight hours per day.[114]

The **United Kingdom** introduced minimum annual targets for smart meter installations for energy suppliers in early 2022.[115] In 2023, the government led a consultation with energy suppliers and other industry stakeholders on its proposal for 2024 and 2025 and set new targets for suppliers to install smart meters in at least 74.5% of households and around 69% of small businesses by the end of 2025.[116]

VIRTUAL POWER PLANTS

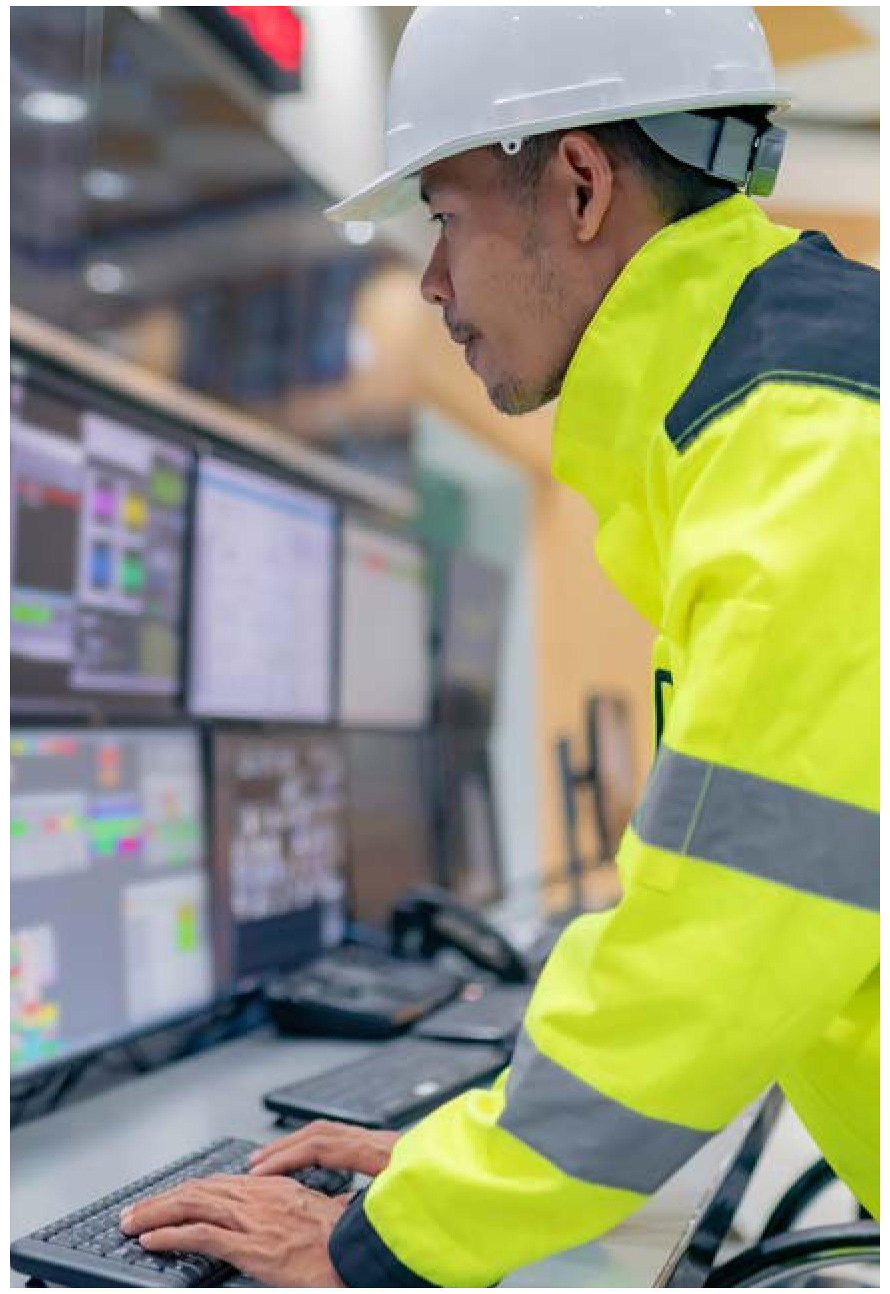
A virtual power plant (VPP) is a cloud-based network that integrates real-time information on distributed energy resources such as solar panels, wind turbines and energy storage systems to operate as a single cohesive entity.[117] Controlled by software, VPPs provide grid services such as frequency regulation, improving the reliability of the grid by pooling resources, facilitating the integration of renewables and optimising the use of distributed energy according to grid needs and market conditions.[118]

The year 2023 was pivotal for the development of VPPs, with substantial advances across regions and companies.[119] (→ *See Table 1.*) The global VPP market value for 2023 was in the range of an estimated USD 1.2 billion to USD 2.5 billion.[120] In Europe, developments were driven largely by company-level advancements, with no new regulatory policies for VPPs during the year. Norway's Statkraft operates one of the region's largest VPPs, claiming more than 10 GW of installed capacity from over 1,000 power generators.[121] Another large VPP system in Europe is operated by the Shell-owned German company Sonnen, which announced that its VPP reached a capacity of 250 MWh.[122] In the United Kingdom, Flexitricity reported that its VPP asset portfolio had grown to more than 1 GW, making it the country's largest flexible energy system.[123]

Table 1.
Networked Capacity of Selected VPP Operators Worldwide, as of Late 2023

VPP Operator (location of headquarters)	Total Network Capacity (MW)
Centrica (United Kingdom)	16,500
Statkraft (Norway)	10,000*
Next Kraftwerke (Germany)	13,500
Enel X (Italy)	9,400
Autogrid (United States)	8,000
Flexitricity (United Kingdom)	1,000
OhmConnect (United States)	3,550
Tesla (United States)	900
AGL (Australia)	316

*Statkraft claims "more than 10 GW installed capacity".
Source: See endnote 119 for this module.



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[i] Through pre-paid metered electricity, consumers pay for electricity before using it, similar to how pre-paid mobile phone plans work. See endnote 111 for this module.

In the **United States**, several states and territories have advanced VPP developments through both policy and company-driven initiatives. Maryland lawmakers directed the Public Service Commission to develop VPP pilot programmes, with utilities required to propose pilots by July 2025.[124] In Colorado, the utility Xcel Energy aimed to set up a 50 MW VPP by the end of 2024 and already has a programme (Renewable Battery Connect) that discharges customer batteries during peak periods for financial incentives.[125] In Puerto Rico, Sunrun was selected by the Puerto Rico Electric Power Authority to deploy a 17 MW solar-plus-storage VPP to enhance the island's energy resilience.[126]

California adopted legislation that directs the California Energy Commission (CEC) and CAISO to estimate the potential of VPPs and support the state's goal of 7 GW of flexible demand by 2030.[127] The CEC's Demand Side Grid Support programme allows private batteries to aid the grid during high demand, with owners of the SolarEdge Home Battery participating in the initiative.[128] OhmConnect and SunPower Corp. launched a VPP in the service areas of California's Pacific Gas and Electric Co.[129] In addition, OhmConnect partnered with Google's Nest Renew to create Renew Home, a 3 GW network that now makes up North America's largest residential VPP.[130]

China's policy framework for VPPs has expanded rapidly under the country's carbon reduction plans. As of 2023, projects were under way in multiple provinces, including Hebei, Jiangsu, Shanghai and Zhejiang.[131] Recent initiatives include Ningxia's VPP control platform, which manages five VPPs across 14 industries, and a smart control platform in Yantai, which connects a 242,000 kilowatt (kW) flexible energy system to State Grid Shandong Electric Power Company and the local State Grid branch through a VPP.[132]

MICROGRIDS

Microgrids hold significant potential for enhancing grid resilience and ensuring power supply during emergencies such as extreme weather events. Renewables-based microgrids usually consist of solar panels or wind turbines (and sometimes hydropower) combined with energy storage systems and smart control.[133] Although microgrids typically operate independently in remote areas, in some cases they can be connected to the larger electricity network and disconnected when necessary.[134] The market for grid-connected microgrids was valued at USD 12.8 billion in 2023 and is expected to grow significantly due to their recognised potential for improving grid reliability[i,135]

In 2023, microgrids were a key component of the GRIPS programme in the **United States**.[136] In **Puerto Rico**, researchers from Oak Ridge National Laboratory are testing a "microgrid orchestrator" that would allow microgrids to form a larger network to increase resiliency and enable the integration of more renewable energy.[137] Networked microgrids can operate independently from the main grid for extended periods, which is vital during prolonged outages caused by severe weather and other natural disasters.[138]

In **Canada**, the national government and the energy utility Hydro-Quebec announced an additional USD 2.7 million (CAD 3.7 million) microgrid in Lac-Mégantic, which can operate connected to the main grid or in isolation.[139] Commissioned in 2021, the microgrid powers around 30 downtown buildings and features more than 2,200 solar panels (a total capacity of 800 kW), 700 kW of battery storage, a centralised control system, energy management tools and a bi-directional EV charging station.[140]

From a market perspective, energy companies have increasingly proposed the model of "microgrids-as-a service" (MaaS) to industries and to commercial and public buildings such as schools, universities, municipalities, hospitals and even jails.[141] The MaaS model consists of a third-party company providing a turnkey service of designing, installing and operating a microgrid on the premises of the customer, and billing for the energy consumed.[142] Examples include the **South Australia** Produce Market (SAPM), which started operating in 2023; the Mbogo Valley Tea Factory in **Kenya**, installed in 2022; and the ABB headquarters in **South Africa**, in operation since 2016.[143]

The market for
grid-connected microgrids
was valued at
USD 12.8 billion in 2023.

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i Note that this number is global and does not reflect the specific share of renewables-based grid-connected microgrids.

ENERGY STORAGE

In 2023, battery storage continued to be the fastest growing energy storage technology, with increased investment and policy attention.

76%	pumped storage share of total utility-scale energy storage
83%	batteries’ share of overall utility-scale storage capacity additions
120%	growth in utility-scale battery storage capacity in 2023

KEY FACTS

- By the end of 2023, 43 jurisdictions had in place policies for energy storage, including regulatory policies, targets, and fiscal and financial incentives.
- China more than tripled its investments in battery storage in 2023.
- Lithium-based technologies continued to dominate the battery market.
- Australia announced plans for the world’s largest pumped storage plant in Queensland, with 5 GW capacity.

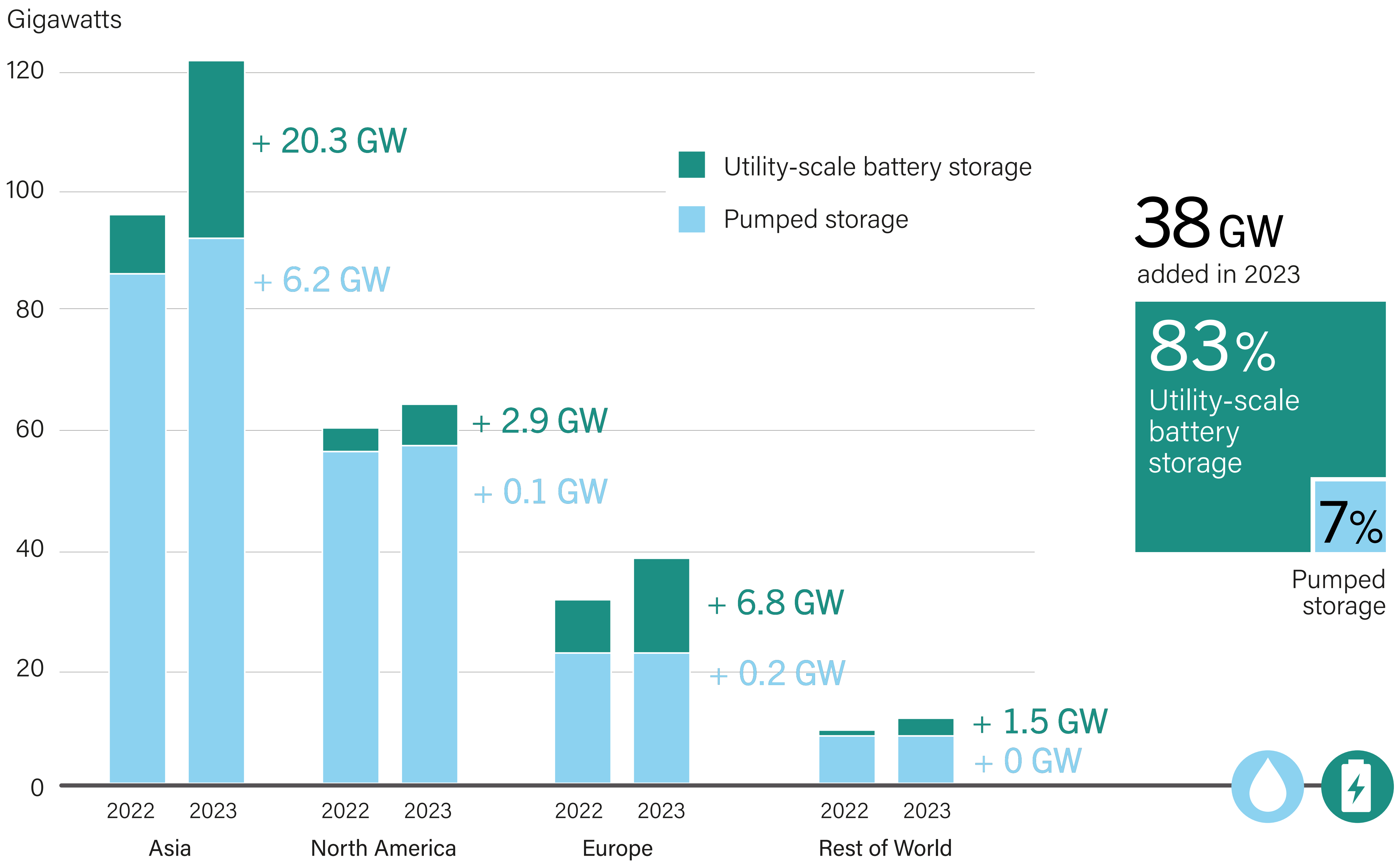
Pumped storage[i] remains the largest energy storage technology, with a total installed capacity of 179 GW in 2023.[144] Global pumped storage capacity additions increased 6.48 GW during the year, down 38% from 2022 additions.[145] The growth in pumped storage worldwide is due in part to rising adoption of variable renewable energy, which requires more storage during off-peak producing times.[146] In many regions, pumped storage is expected to remain the most cost-effective option for large-scale utility storage for the foreseeable future.[147]

Although no global datasets on pumped storage investments are available, investments in individual projects in 2023 included the Seminoe Project in the US state of Wyoming (USD 2.5 billion), the Zhejiang Jinyun Project in China (USD 1.45 billion, or CNY 10 billion) and the Gouvaes Project in Portugal (USD 1.7 billion).[148] Australia announced plans for the world's largest pumped storage plant in Queensland, which was initiated with USD 23.8 million (AUD 35 million) in public funds from the Queensland Government.[149]

For **battery energy storage**, lithium-based technologies continued to dominate, although flow batteries also have been commissioned.[150] Average prices for lithium-ion battery packs fell to a new record low of USD 139 per kWh in 2023, following a small increase in 2022.[151] (This category is dominated by EV batteries but also includes stationary storage and electric buses; it does not cover balance-of-system costs for utility storage.[152])

In 2023, global battery storage capacity grew 120% to reach 55.7 GW.[153] In China, battery storage capacity increased 250% to reach 27.1 GW, up from 7.8 GW in 2022.[154] In the United States, capacity grew from 9.3 GW in 2022 to 16.2 GW in 2023, and California was home to more than 5 GW of battery storage capacity, a tenfold increase from 2020.[155] The United Kingdom was the largest European market, with 3.6 GW of installed capacity, followed by Germany (1.7 GW) and Ireland (0.4 GW).[156] Other important battery storage markets were Australia, with a total installed capacity of 1.8 GW, the Republic of Korea with 1.1 GW and Japan with 0.6 GW.[157] (→ *See Figure 3.*)

FIGURE 3.
Utility-scale Storage Capacity, by Type and Region, 2022 and 2023



Source: See endnote 157 for this module.

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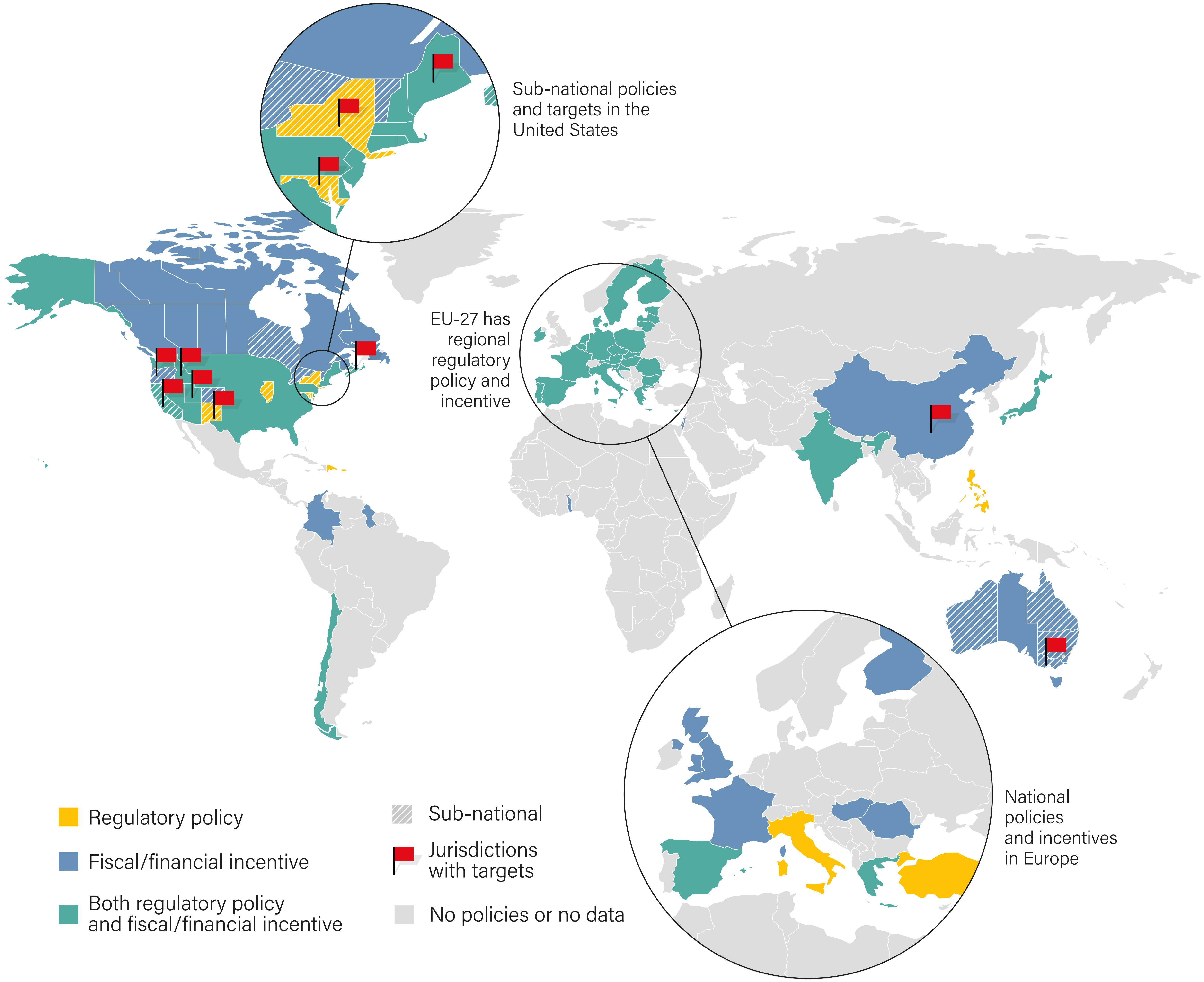
[i] Pumped storage is a form of hydroelectric energy storage that uses two water reservoirs positioned at different heights. Energy is generated as water flows down from the upper reservoir to the lower one, driving a turbine in the process.

Dedicated policy support for battery storage exists mostly in the form of targets and incentive programmes.[158] As of 2023, 11 national and sub-national jurisdictions had established **targets** specifically for energy battery storage.[159] (→ *See Figure 4.*) Under the EU's New Renewable Energy Directive, several Member States updated their targets for energy storage when submitting their updated National Energy and Climate Plans in 2023.[160] Greece, for example, set a target for 3.1 GW of battery storage and 2.2 GW of pumped storage capacity by 2030.[161]

FIGURE 4.
National and Sub-National Targets, Policies and Fiscal/Financial Incentives for Renewable Energy Storage, 2023

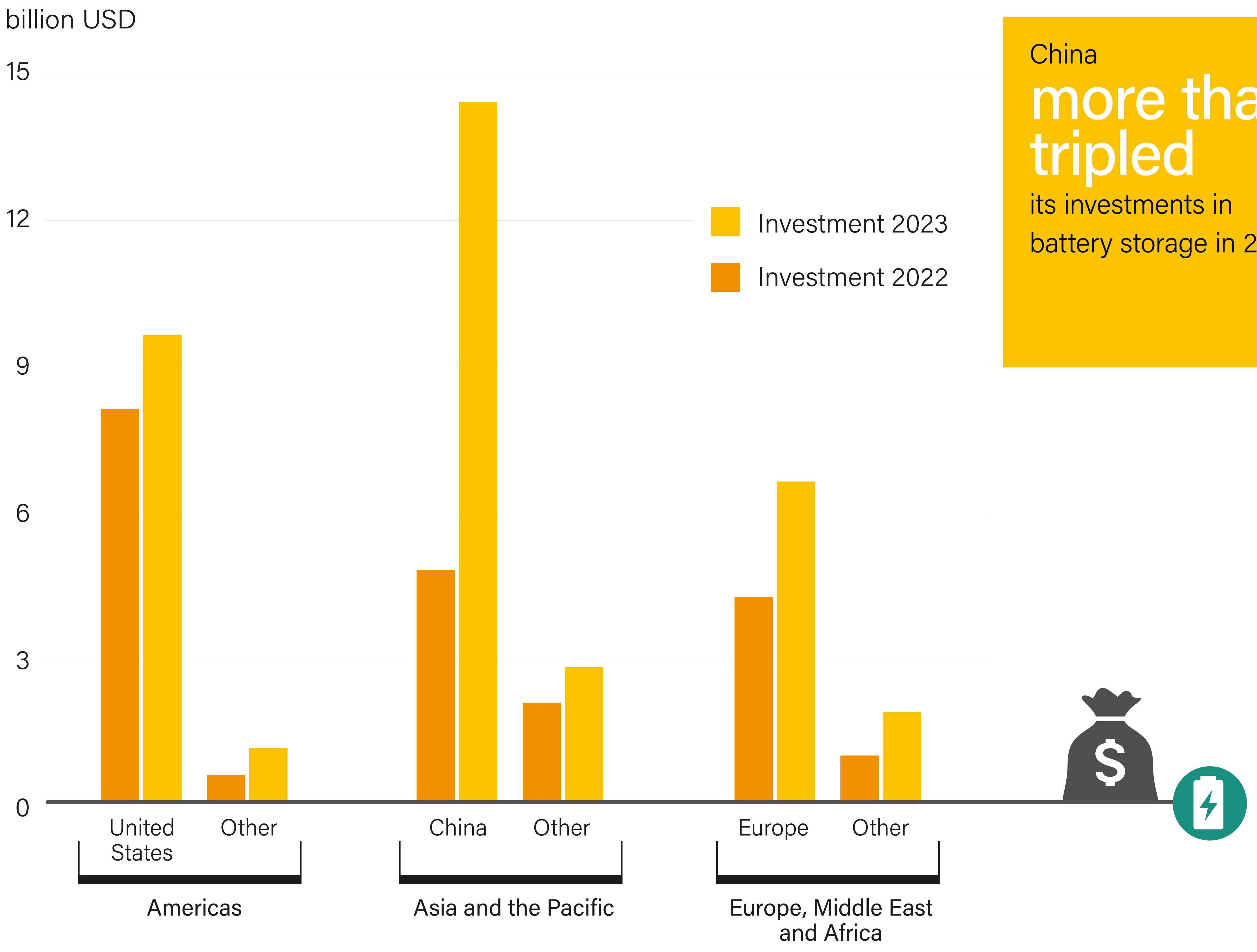


11 jurisdictions
had battery storage targets as of 2023.

Note: Figure does not show tenders for energy storage. Most countries had storage policies and projects for the power sector only as of 2023; however, the UK financial incentive was for heat, power, and hydrogen, and the US programme was for hydrogen. Technologies for which storage policies and programmes existed included battery energy storage systems and pumped storage systems. Some national and sub-national jurisdictions had storage policies and projects at the company level: Australia, Belgium, Benin, Chile, China, Greece, India, Poland, Portugal, Saudi Arabia, Switzerland, the United Kingdom and the United States. Some jurisdictions also had projects, programmes or plans for renewable energy storage: China, Colombia, India, Japan, Lithuania, Quebec (Canada), Queensland (Australia), Spain, Sweden, Tazmania (Australia), the United Kingdom and Viet Nam. India, the Philippines and the United States had new or revised regulatory policies in 2023, and Israel and the US states of Colorado, Missouri and Vermont had new or revised fiscal/financial policies.

Source: REN21 Policy Database. See endnote 159 for this module.

FIGURE 5.
Investment in Battery Storage by Major Country/Region, 2022 and 2023



China
more than tripled
its investments in battery storage in 2023.

Source: See endnote 170 for this module.

As of 2023, 18 national and sub-national jurisdictions had regulatory policies for energy storage, and 33 jurisdictions had **fiscal and financial incentives** to support battery storage.[162] (→ *See Figure 4.*) Hungary announced a USD 337 million (HUF 120 billion) investment support scheme through grants to support the construction of utility-scale battery storage and its operation for at least 10 years.[163] Spain awarded USD 166 million (EUR 150 million) in subsidies for 36 battery storage projects that are combined with renewable energy power plants, as well as USD 310 million (EUR 280 million) in grants for stand-alone battery storage, thermal energy storage and pumped storage projects.[164]

In March 2023, the European Commission released a set of guidelines on energy storage, with proposed policy measures aimed at facilitating wider implementation of electricity storage solutions across the region.[165] In early 2024, Italy released new regulations on the Electric Storage Capacity Procurement Mechanism, which is expected to encourage large capacity auctions for grid-scale battery and power-to-gas storage.[166] South Africa's Renewable Energy Master Plan specifies a strategy for the country's energy storage value chain.[167] At the sub-national level, the US states of California, Illinois, Maryland and New Mexico have implemented policies to refine the interconnection standards for distributed energy resources, with special attention to battery storage.[168]

Investment in battery storage worldwide continued its substantial growth trend, increasing 76.8% in 2023 to reach USD 36.3 billion.[169] China dominated with USD 14.5 billion (up 203%), followed by the United States (USD 9.6 billion; up 18.8%) and Germany (USD 3.3 billion; up 61.2%).[170] (→ *See Figure 5.*) Energy storage investments also surged in Italy (reaching USD 2.2 billion) and Australia (USD 1.0 billion).[171]

Growth in battery storage investment in China was due mainly to favourable economics for utility-scale battery storage and to strong policy support.[172] In 2023, construction began on the country's first combined compressed air and lithium-ion battery storage power station in Dingxi City (Gansu Province), with a total investment of USD 112 million (CNY 812 million).[173] In the United States, the Inflation Reduction Act and the Bipartisan Infrastructure Law are expected to improve long-term regulatory certainty for investors and to reduce capital costs for battery storage, creating a more favourable environment.[174]

SECTOR COUPLING

Sector coupling refers to the integration of energy supply and demand across different electricity, heat and transport applications.

48% increase in total public and private EV charging points in 2023

55 countries with a renewable hydrogen roadmap by the end of 2023

KEY FACTS

- As of 2023, 38 jurisdictions worldwide had regulatory policies, targets or fiscal and financial incentives for EV charging infrastructure.
- A total of 13 jurisdictions worldwide had regulatory policies, targets or fiscal and financial incentives for renewable hydrogen.
- In France, a first-ever corporate power purchase agreement was signed between a wind energy company and a renewable hydrogen producer.

Sector coupling refers to the integration of energy supply and demand across different electricity, heat and transport applications. This is essential to secure energy supply and to increase the share of renewables by providing the system flexibility required by variable renewable energy.[175] For example, using excess power generation at peak times can optimise system operations and increase efficiency.[176] This is achieved by linking the power sector with the heating and cooling sector (to meet thermal needs) and with the transport sector (to charge EVs).

Sector coupling requires precise co-ordination, which can be achieved through digitalisation, such as the development of smart grids and smart network infrastructure.[177] Another aspect of sector coupling is power-to-hydrogen transformations, where hydrogen production can harness excess renewable electricity. Hydrogen production through electrolysis can offer flexibility to electricity markets and can be used in fuel cells for heating, cooling and transport applications.[178]

ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

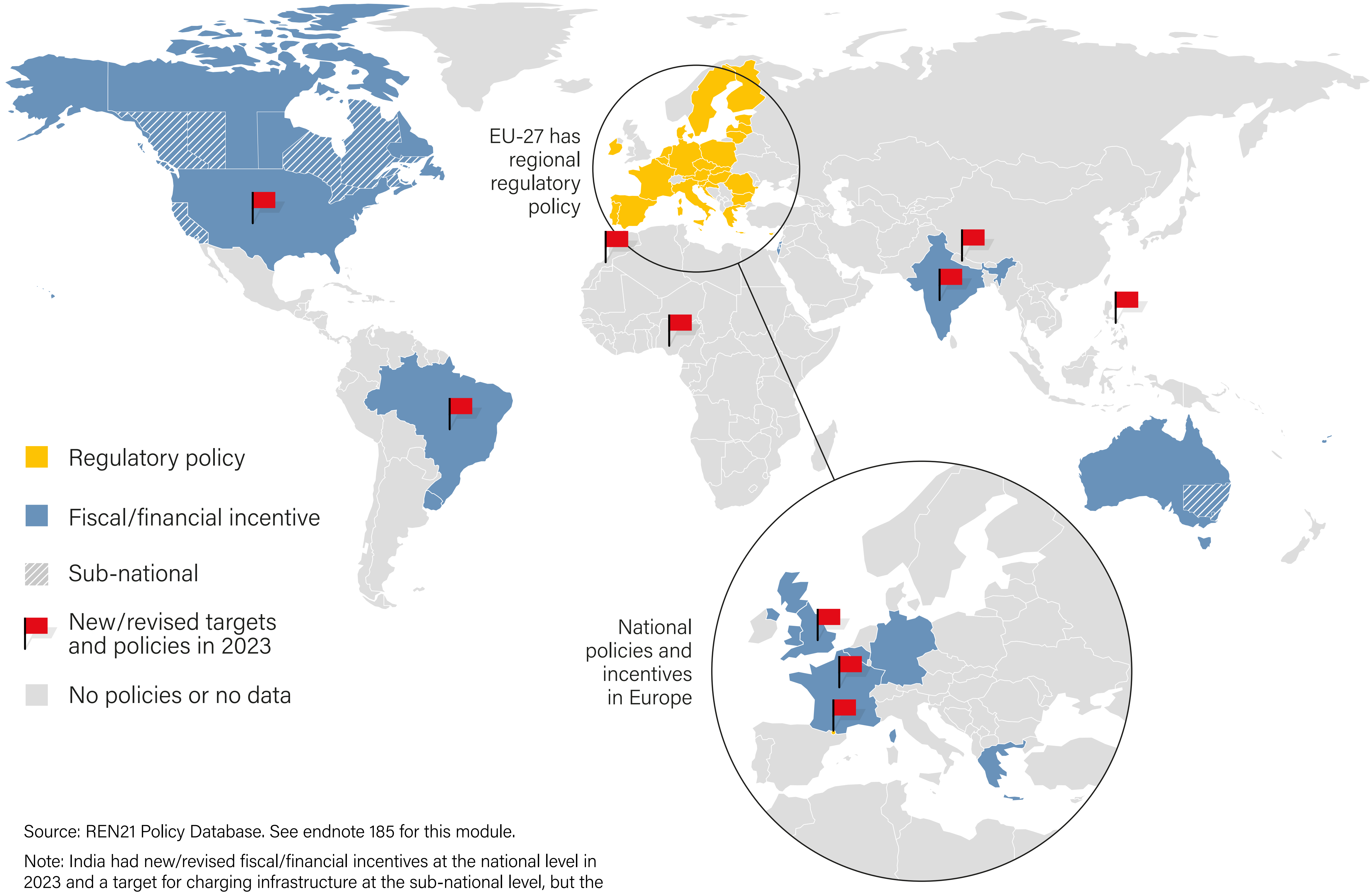
The uptake of electric vehicles influences the loading on power grids, affecting how much of the grid capacity is utilised and potentially leading to fluctuations in electricity demand.[179] While EV uptake entails an increase in electricity consumption and possible uncertainty about peak hours, it also presents significant opportunities for enhancing grid flexibility.[180] Time-shifted charging can optimise the timing of EV charging, helping to balance demand, reduce peak loads and improve grid efficiency.

Bi-directional charging offers further potential to support grid stability by allowing EVs to send power back to the grid when needed.[181]

Global deployment of EV charging infrastructure for light-duty vehicles surged in 2023 to around 40 million public and private charging points, up from around 27 million in 2022.[182] Most charging points have been installed in private homes, although the distribution varies greatly by region depending on density, urban and rural household structures, and access to public charging facilities.[183] Dedicated charging infrastructure for heavy-duty vehicles is still in its infancy.[184]

As of 2023, 3 jurisdictions worldwide had **regulatory policies** for EV charging infrastructure, 21 jurisdictions had **fiscal and financial incentives**, and 33 jurisdictions had **targets** for future infrastructure development.[185] (→ *See Figure 6.*) During the year, Malaysia introduced a set of tax incentives for EV charging infrastructure, including 100% income tax exemptions to 2032 for manufacturers of charging equipment to ensure affordable local production.[186] Poland provided funding to install 41 EV charging stations in national parks.[187] Estonia is providing subsidies of 30% to 50% for the cost of charging infrastructure as part of a USD 86 million (EUR 80 million) subsidy scheme for building retrofits.[188] Latvia plans to build 2,060 new EV charging points as part of a larger distribution system update from the national distribution company.[189] The US Alternative Fuel Infrastructure Tax Credit, which came into effect in January 2023, includes grants and tax credits for commercial and residential customers to install EV charging points.[190]

FIGURE 6.
National and Sub-National Targets and Policies for Electric Vehicle Charging Infrastructure, 2023



Source: REN21 Policy Database. See endnote 185 for this module.

Note: India had new/revised fiscal/financial incentives at the national level in 2023 and a target for charging infrastructure at the sub-national level, but the exact jurisdiction was not specified.

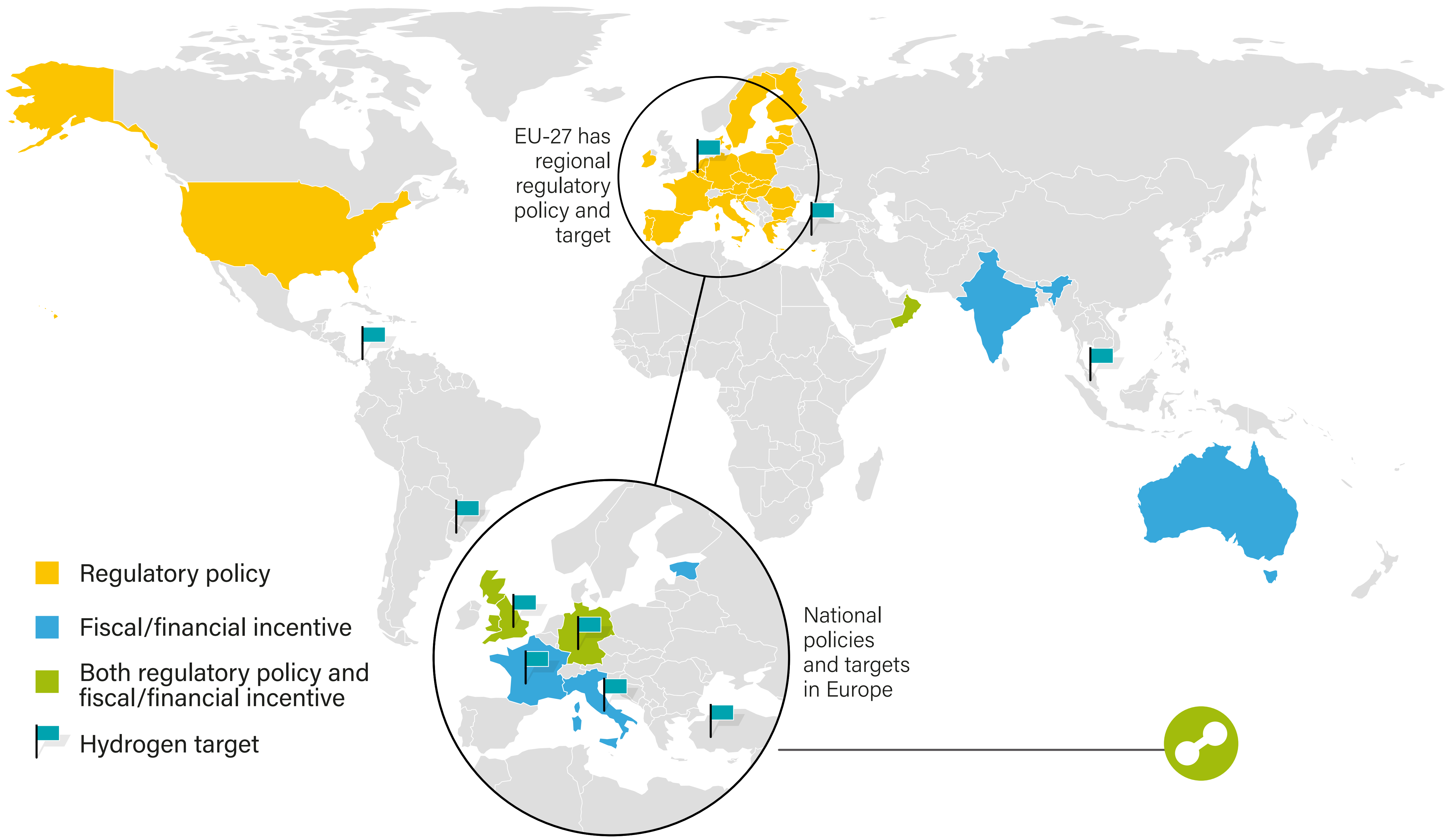
In Brazil, the Senate proposed a bill mandating all fuelling stations to be equipped with EV chargers.[191] Denmark is providing financing for EV charging stations for housing associations.[192] India allocated USD 95 million (INR 8 billion) in funding to install 7,432 EV charging stations across the country.[193] Countries also have experimented with vehicle-to-grid policies, although few such policies are actually in place. China announced new rules to integrate EVs to the grid, including incentives to charge the vehicles during offpeak hours and sell power back to the grid.[194] South Australia has trialled similar incentives.[195]

RENEWABLE HYDROGEN

Renewable hydrogen continued to receive increasing policy attention in 2023, with five countries and the EU having regulatory policies and nine countries having fiscal/financial incentives for renewable and mixed[i] hydrogen.[196] By year's end, a total of 55 countries had in place a renewable hydrogen strategy or roadmap, 7 of which were announced or revised in 2023.[197] (→ *See Figure 7.*) Oman published a hydrogen strategy that targets 1 million tonnes of renewable-based hydrogen production annually by 2030 and 7.5 million tonnes by 2050.[198] Türkiye unveiled a National Hydrogen Strategy that includes a target to reach 70 GW of electrolyser capacity by 2053, with a strong focus on renewable hydrogen (while also including other sources of hydrogen production).[199] Germany updated its National Hydrogen Strategy, and Argentina, Estonia and India also announced hydrogen strategies.[200]

Around
40 million
public and private EV charging points were available globally as of 2023.

FIGURE 7.
Hydrogen Targets and Policies in Selected Countries, as of End-2023



Note: Hydrogen targets are for share of production of renewable hydrogen, imports of green hydrogen and/or use of hydrogen in heavy vehicles and in industry. Hydrogen policies are for renewable and mixed hydrogen. Mixed hydrogen refers to hydrogen produced using both renewable and non-renewable energy sources. Of the 16 countries with Hydrogen targets and policies, 5 have them for the production of mixed hydrogen and 11 have them for the production of renewable hydrogen.

Source: REN21 Policy Database. See endnote 197 for this module.

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[i] Mixed hydrogen refers to hydrogen produced using both renewable and non-renewable energy sources.

In 2023, the EU launched the European Hydrogen Bank to initiate the market for hydrogen, providing USD 883 (EUR 800 million).[201] In addition, the update of the EU Gas Package strengthened regulatory support for the development of hydrogen; this included certification for low-carbon gases, the establishment of the European Network of Network Operators for Hydrogen, and joint planning of the networks for electricity, gas and hydrogen.[202] The United Kingdom released details on a support mechanism for low-carbon hydrogen production to make up the gap in operating costs between low- and high-carbon fuels for 15 years.[203] The United States released regulations in December 2023 on the Clean Hydrogen Production Credit under the Inflation Reduction Act, and also announced USD 7 billion in funding for seven regional clean hydrogen hubs.[204]

Some countries have implemented **tenders and auctions** that include hydrogen. In 2023, Denmark launched a power-to-X[i] tender of USD 181 million (DKK 1.25 billion) for renewable hydrogen production through electrolysis.[205]

Investment in hydrogen increased 203% in 2023, reaching USD 10.4 billion.[206] Most of this was for electrolysers (84.1%) and thermochemical hydrogen[ii] (13.4%).[207] The bulk of hydrogen production worldwide continues to come from fossil fuel sources; by comparison, renewable-based hydrogen is two to three times more expensive to produce, which has hampered investment interest.[208]

Most ongoing renewable hydrogen production is pre-commercial, with China experiencing the strongest growth in electrolyser capacity.[209] Globally, projects depend heavily on public financial support, and the industry faces significant uncertainty, despite strong growth and optimism. Not all initiatives have been continued or translated to industrial operations.[210] However, in France, a first-ever corporate power purchase agreement was signed between a wind energy company and a renewable hydrogen producer, securing funds to repower a 15 MW wind farm and providing up to 46 gigawatt-hours per year.[211] Additionally, in a microgrid environment, the utility PG&E collaborated with Energy Vault to demonstrate a combination of long-term hydrogen and short-term battery storage in California.[212]

The bulk of the **world's hydrogen production** continues to come from fossil fuel sources.

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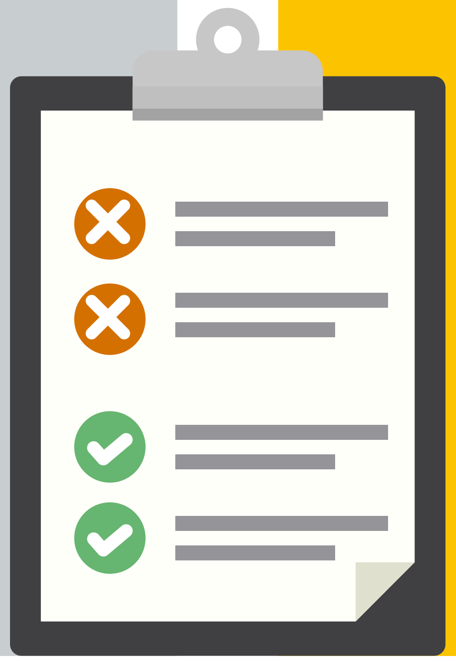
[i] Power-to-X refers to the linking of the electricity sector with other sectors such as heating, cooling, transport and industry to increase integration of variable renewable electricity. It also uses surplus electricity in other sectors and stores it (in batteries, as thermal energy, as renewable hydrogen) for later use.

[ii] "Thermochemical processes use heat and chemical reactions to release hydrogen from organic materials, such as fossil fuels and biomass, or from materials like water. Water can also be split into hydrogen and oxygen using electrolysis or solar energy." See endnote 207 for this module.

CHALLENGES

- **Time frames for developing grid infrastructure are longer** than those for developing renewable power capacity, resulting in grid congestion, connection queues and curtailment.
- **The capital-intensive nature of grid-related infrastructure projects** leads to affordability issues, especially in emerging and developing economies.
- **Complex projects** require integrated planning and involve a wide range of stakeholders.



OPPORTUNITIES

→ **Policy attention and investment** in the optimisation and expansion of grid infrastructure are increasing.

→ **Growth is occurring in utility-scale battery storage capacity,** as well as in electric vehicle charging infrastructure, through targets and policies.

→ **Technology developments include grid-enhancing technologies,** virtual power plants, microgrids provide tools for grid optimisation and stabilisation.

ENDNOTES | ENERGY SYSTEMS AND INFRASTRUCTURE

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