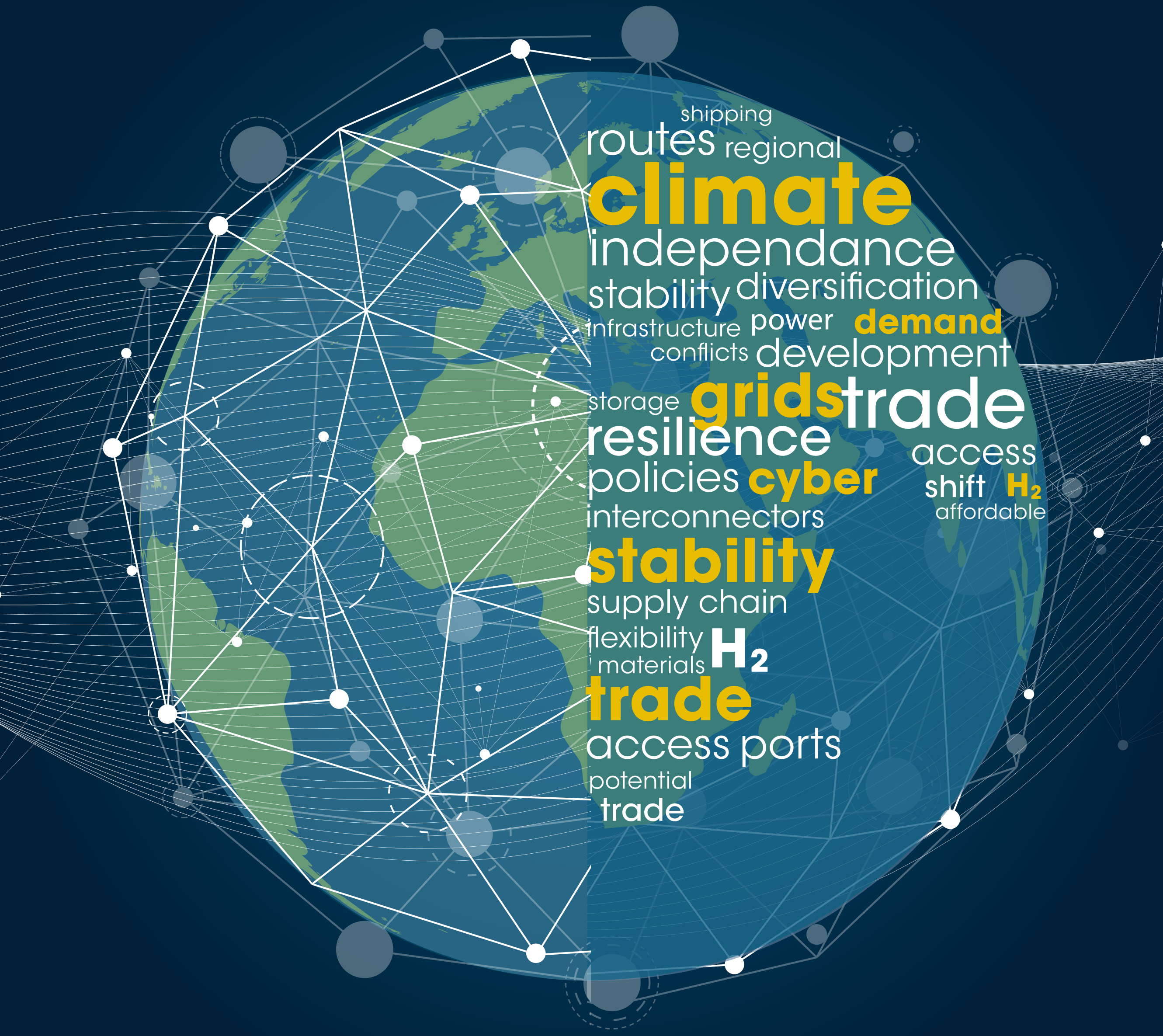
IRENA
International Renewable Energy Agency

GEOPOLITICS OF THE ENERGY TRANSITION

ENERGY SECURITY



IRENA
International Renewable Energy Agency

© IRENA 2024
Unless otherwise stated, material in this publication may be freely used, shared, copied, reproduced, printed and/or stored, provided that appropriate acknowledgement is given of IRENA as the source and copyright holder. Material in this publication that is attributed to third parties may be subject to separate terms of use and restrictions, and appropriate permissions from these third parties may need to be secured before any use of such material.

ISBN: 978-92-9260-599-5

CITATION: IRENA (2024), *Geopolitics of the energy transition: Energy security*, International Renewable Energy Agency, Abu Dhabi.

For further information or to provide feedback: publications@irena.org

This report is available for download: www.irena.org/publications

ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future. It serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

www.irena.org

This publication was supported by voluntary contributions from the Governments of the Netherlands and Norway.

DISCLAIMER

This publication and the material herein are provided “as is”. All reasonable precautions have been taken by IRENA to verify the reliability of the material in this publication. However, neither IRENA nor any of its officials, agents, data or other third-party content providers provides a warranty of any kind, either expressed or implied, and they accept no responsibility or liability for any consequence of use of the publication or material herein.

The information contained herein does not necessarily represent the views of all Members of IRENA. The mention of specific companies or certain projects or products does not imply that they are endorsed or recommended by IRENA in preference to others of a similar nature that are not mentioned. The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

ACKNOWLEDGEMENTS

This report was developed under the supervision of Elizabeth Press (Director, IRENA Planning and Programme Support), who co-authored the report with Yana Popkostova and Thijs Van de Graaf (IRENA consultants) with substantive support from Ellipse Rath and Gerald Tagoe.

The authors are grateful for the reviews, inputs and support provided by IRENA colleagues Roland Roesch, Michael Taylor, Francisco Boshell, Ricardo Gorini, Paul Komor, Imen Gherboudj, Adrian Gonzalez, Sibghat Ullah, Francis Field, Kathleen Daniel, Stephanie Clarke, Anastasia Kefalidou, Celia García-Baños, Jaidev Dhavle and Hannah Sofia Guinto.

Internal peer review was provided by Caroline Ochieng, Emanuele Bianco, Karsten Sach (IRENA consultant), Michael Renner, Mirjam Reiner, Raul Alfaro Pelico, Safiatou Alzouma and Stefano Marguccio. External peer review was provided by Andras Rozmer (EEAS), Annabelle Livet (Foundation for Strategic Research), Benjamin Gibson (Ørsted), Daniel Scholten (University of Minnesota), Hans Olav Ibrekk (Norwegian Ministry of Foreign Affairs, Section for Energy, Climate and Environment), Holger Klitzing (Federal Foreign Office, Germany), Indra Overland (NUPI), Irina Patrahau (HCSS), Ligia Noronha (UNEP), Olga Khakova (The Atlantic Council), Paula Kivimaa (Finnish Environment Institute [SYKE], Piyush Verma (UNDP), Ruud Kempener (European Commission) and Saito Kazuhiko (Ministry of Foreign Affairs, Japan).

The report was edited by Steven Kennedy. Design was provided by weeks.de Werbeagentur GmbH.

© ljubaphoto; iStock

ABBREVIATIONS

ACC	air cooled condenser
COP	Conference of the Parties
CRM	critical raw materials
EJ	exajoule
ESG	environmental, social and governance
EU	European Union
EVs	electric vehicles
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GW	gigawatt
H_2	hydrogen
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPRs	intellectual property rights
IRENA	International Renewable Energy Agency
LFP	lithium-iron phosphate
NATO	North Atlantic Treaty Organization
NMC	nickel-manganese-cobalt
OECD	Organisation for Economic Co-operation and Development
PV	photovoltaic
SDG	Sustainable Development Goals
TFEC	total final energy consumption
TW	terawatt
TWh	terawatt-hour
(U)HVDC	(ultra) high voltage direct current
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UF6	uranium hexafluoride
US	United States
USD	United States dollars
WETO	World Energy Transitions Outlook
WIPO	World Intellectual Property Organization

© Philip Lange; shutterstock

FOREWORD

The essential role of renewables in creating more resilient, inclusive and cleaner energy systems is undisputed. COP28 underscored this with a pledge to triple renewable capacity and double energy efficiency by 2030, while transitioning away from fossil fuels. This pathway, adopted from IRENA's *World Energy Transitions Outlook*, represents our only option to course-correct within the next six years to stay on the 1.5°C pathway.

The acceleration of a renewable-based transition relies on our collective ability to prioritise actions around key enablers such as the modernisation and expansion of infrastructure, policy and market adaptation, and institutional and human capacities. All these areas are strongly linked to energy security, which is still predominantly viewed through the lens of a fossil fuel-dominated era and its geopolitical landscape. Given the rise of renewables, IRENA's members have requested an exploration of the implications of this shift for energy security.

This report builds on IRENA's geopolitics of the energy transition series, and leverages extensive IRENA knowledge of a wide range of technical, socio-economic and climate issues.

The report advises that policymakers should not merely transpose thinking from the fossil fuel era to a renewables-based system. It identifies multiple issues that should be systematically considered to guide national decision making on resource endowments and comparative advantages. This is particularly crucial as governments make significant investments in infrastructure for systems that are increasingly electrified, digitalised and decentralised. The report places the well being of people and the planet at the centre of the evolving energy security narrative. Ultimately, it recognises that addressing energy security is as much a political endeavour as it is a technical one.

This report was developed under the Collaborative Framework on the Geopolitics of Energy Transformation. I would like to extend my gratitude to the IRENA membership for their support of this work and to the many experts from academia, think tanks, international organisations and the private sector who provided insightful input and feedback on this report. It is my hope that this new analysis will spark an informed and constructive dialogue on the evolving nature of energy security in the era of renewables.

Francesco La Camera
Director-General, IRENA

TABLE OF CONTENTS

© Christopher Ames ; iStock

LIST OF FIGURES

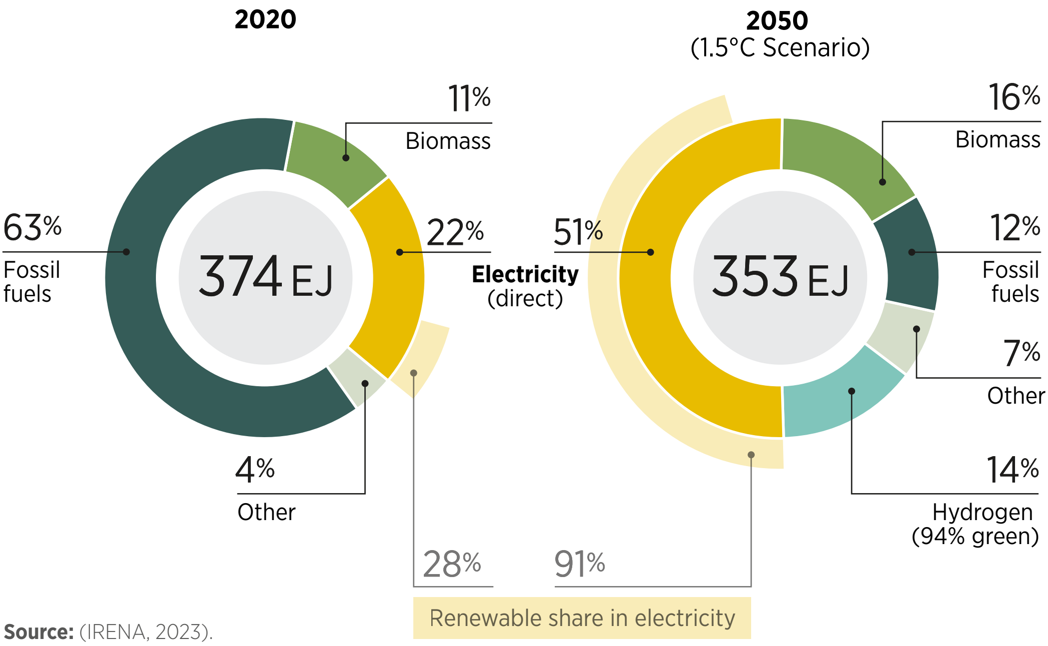
LIST OF BOXES

© Crovik Media; shutterstock

SUMMARY FOR POLICY MAKERS

Transitioning from fossil fuels to renewable energy yields more electrified, decentralised and digitalised energy systems. Systems based on renewable energy, including green hydrogen and sustainable biomass, lend themselves to high rates of electrification and efficiency. According to IRENA's 1.5°C scenario, electricity is projected to become the primary energy carrier in the future, with its share more than doubling from 22% today to 51% by 2050 (Figure S.1). By 2050, both biomass and hydrogen are expected to constitute larger portions of the total energy consumption than fossil fuels.

FIGURE S.1 Total final energy consumption by energy carrier under IRENA's 1.5°C scenario, 2020 and 2050



Source: (IRENA, 2023).
Note: EJ = exajoules.

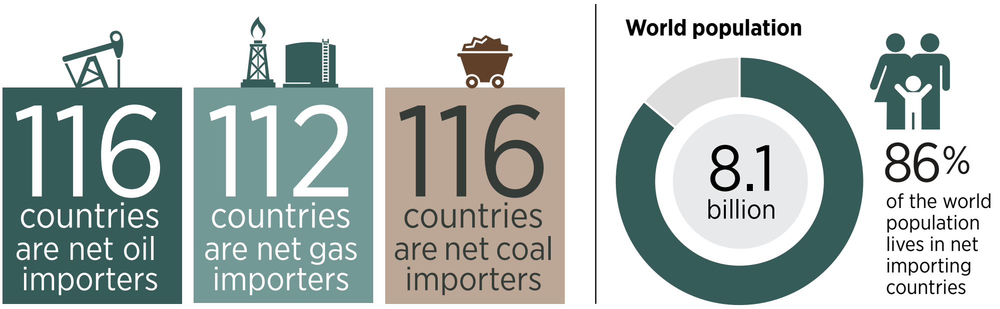
The share of renewable energy in the global energy mix would increase from 16% in 2020 to 77% by 2050 in IRENA's 1.5°C scenario. Total primary energy supply would remain stable due to increased energy efficiency and growth of renewables. Use of renewables would increase across all end-use sectors, while a high rate of electrification in sectors such as transport and buildings would require a twelve-fold increase in renewable electricity capacity by 2050, compared to 2020 levels.

Tripling renewables and doubling efficiency by 2030 form the central pillar of the decarbonisation strategy, also affirmed at COP28 in December 2023. IRENA estimates that an additional 11 terawatts (TW) of renewable power capacity will be required to cut emissions by 43% by 2030 in line with the recommendations of the Intergovernmental Panel on Climate Change (IPCC). The most viable approach within this timeline involves aggressively deploying renewable and efficiency technologies, reducing reliance on fossil fuels, and innovating for action beyond 2030.

Every country has some form of renewable potential it can harness, thereby enhancing its energy resilience, independence and control, and reducing exposure to volatile fossil fuel prices. In 2022, 86% of the global population lived in countries that were net importers of fossil fuels. The shift to renewables from local sources will boost self-sufficiency, shifting energy dependencies from the global to the regional level and making most countries less susceptible to geopolitical disruptions. By conventional standards of energy security, this promises enhanced stability and resilience, while improving balance of payment and macroeconomic benefits.

©janiecbros; iStock

FIGURE S.2 Share of countries and global population dependent on net imports of fossil fuels



Source: (UN Comtrade Database, 2022).

Transitioning away from fossil fuels is set to alter global trade, leading to a substantial regionalisation of energy trade. Approximately 40% of maritime cargo today is made up of fossil fuels, and shipping heavily relies on these fuels. Transitioning away from oil, gas and coal will reduce long-distance trade in energy. Electrification will promote cross-border trade and clean energy commodities such as green hydrogen will not be traded in volumes comparable to fossil fuels, or over such great distances. Going forward, global trade in clean energy-related technologies or semi-finished products is expected to diversify and intensify.

New trade flows in electricity, hydrogen, materials and clean technologies will emerge, differing significantly from traditional fossil fuel dependencies. Disruptions in most of these areas would not immediately affect end-users' energy security. Interruptions in electricity, however, would be instantaneous, changing the nature of energy security policy where cross-border trade is introduced or expanded compared to fossil fuels.

Cross-border trade in electricity fosters mutual benefits, contrasting the asymmetric dependencies seen in oil and gas. Given that the electricity trade may flow in both directions, it should be viewed through the lens of interdependency and mutual benefits. This is evident in the largely integrated EU electricity market, where all 27 member states, including net exporters, benefit from imports. In 2023, none of the EU member countries were exporters all of the time. The interconnectors that facilitate this trade can thus be considered channels for greater integration and co-operation, but such a view implies considerable political trust.

There is a need for a reassessment of what constitutes a strategic sovereign asset. With the rise in electrification, interconnectors and electrical grids become vital for energy security. The same can be said for emerging green energy carriers and locations for seasonal storage. The operation and safety of these assets will play a pivotal role in how energy is traded and secured across borders. This shift requires policy makers to review the ownership and security of energy infrastructure, as well as access to and control of that infrastructure.

Green hydrogen and products derived from it could play an important role in energy security. Producing hydrogen from local renewable sources can reduce reliance on imported fossil fuels, particularly in industry and sectors difficult to decarbonise. There is still a lot of uncertainty regarding the extent to which hydrogen will be traded in large quantities across borders or if industrial activities will shift to renewable-rich areas. In both cases, trade flows will ensue, which would benefit from efforts to diversify suppliers and supply routes as well as efforts to boost resilience such as through storage and contingency planning.

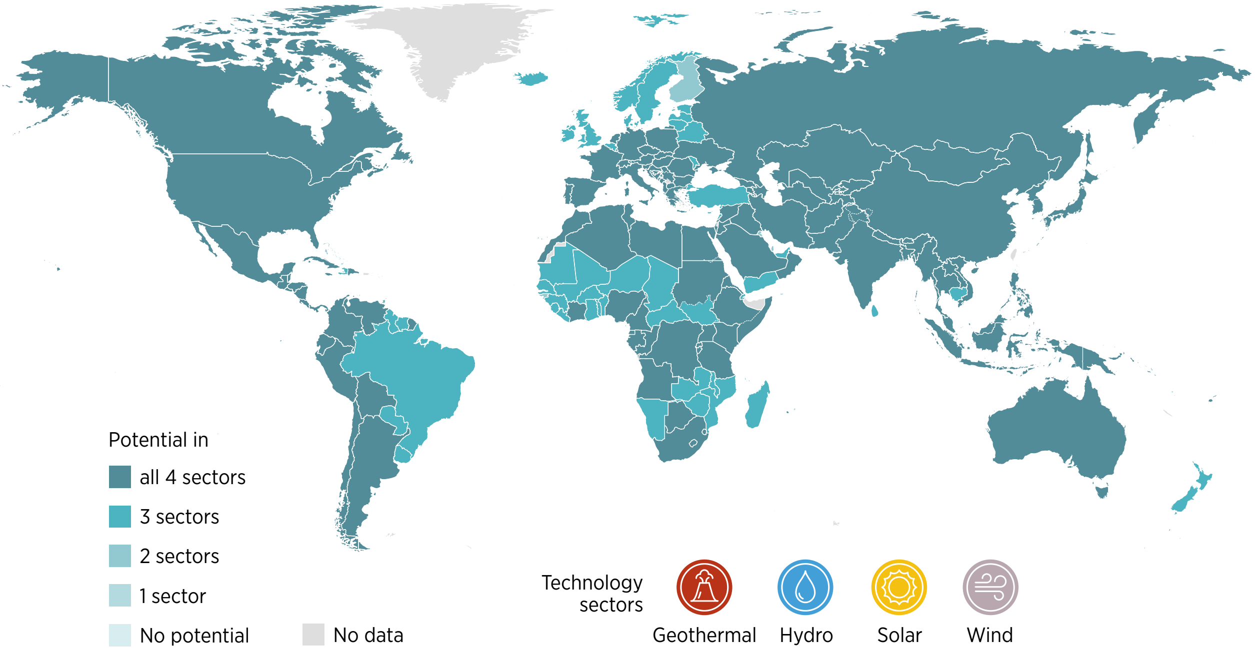
Critical materials, as key inputs to energy technology manufacturing, require attention in the short to medium term due to the high concentration of their supply chains. Diverse and resilient supply chains are essential for the energy transition and both mining and processing volumes and locations are already expanding. Innovation is already relieving the pressures currently being felt in markets and, from the next decade, recycling and circular economy will play a greater role. Continued support for R&D to improve efficiency, find alternatives and shape product design with circularity in mind can reduce long-term vulnerabilities and risks.

No country masters every aspect of clean technologies, so it is essential to consider the impact of domestic policies within a broader web of interdependence. A renewables-dominated future will see energy security focus shift to trade in technologies or semi-finished products. However, the pattern of technology dependency in that system will be vastly different from what it has been in the fossil fuel-dependent world. For instance, most jobs in solar PV are "downstream", as more workers install solar panels than build them. In that context, tariffs and other trade protection measures may have an adverse impact of threatening local jobs.

While renewable resources remain largely unaffected by geopolitical interruptions, harnessing them depends on availability of technologies and finance at scale. This can be challenging for many developing countries due to a lack of access to technology and the prohibitively high cost of capital. Therefore, facilitating technology transfers and ensuring access to intellectual property rights (IPR) is needed to encourage widespread deployment of renewables and to promote equitable development.

Developing nations can enhance the resilience of regional and global energy markets while improving their own economic and energy security, if access to technology and finance is provided to them. Doing so not only fosters domestic growth but can position these nations as competitive players in the global clean technology market. Their integration into the global green economy can favour a more equitable distribution of benefits and technological advancements and help in reducing dependency on a small number of countries, thus making energy markets more resilient.

FIGURE S.3 Techno-economic potential of geothermal, hydro, solar and wind



Source: (IRENA, 2024a).

Notes: Figure is based on IRENA Global Atlas datasets. Only geothermal, hydro, solar and wind sources are included. Data for calculating the techno-economic potential of bioenergy and marine sources is currently unavailable.

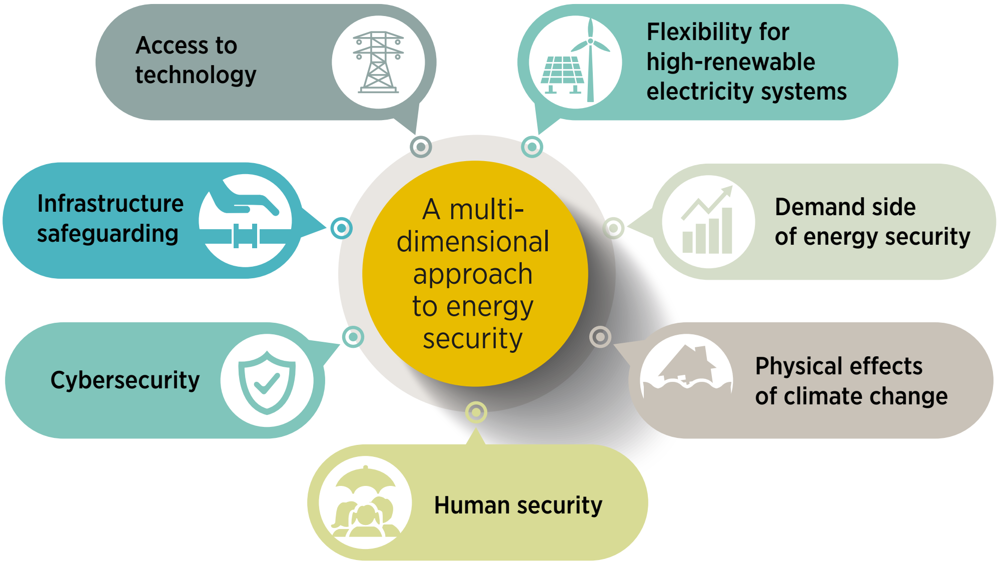
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Energy security in renewables-based systems requires multi-dimensional thinking. The energy transition represents the creation of a new energy system, not just the substitution of one set of fuels for another. Reflexively transposing the geopolitical considerations of the fossil fuel era to the era of renewable energy could lead to significant oversights and ill-considered investments. The systemic nature of the ongoing transition and its wide-ranging social and economic impacts warrant holistic thinking.

Technology – not fuels – will play the dominant role in renewables-dominated systems. In the evolving global energy landscape, technology supply chains will be exposed to geopolitical disruptions and uncertainties, their exposure magnified by the complex web of connections. Ensuring access to technology will also depend on enhancing supply chain resilience. Given the need to decarbonise the global economy and the critical role of energy for industrialisation and development in the global south, resilience is an indispensable part of energy security frameworks.

In an electricity-dominated energy system, flexibility is a critical aspect of energy security. Renewable power is increasingly dominated by solar and wind power, and, in 2023 alone, 98% of the new capacity added globally involved one of these technologies. As the share of these and other variable sources of energy grows, flexibility grows in importance giving the ability of power systems to respond to changes in demand and supply. Flexibility increasingly depends on infrastructure that is interconnected across borders, a state of affairs that implicates regulatory frameworks and political relations.

FIGURE S.4 A multi-dimensional approach to energy security




© show999; iStock

Energy demand, often overlooked in discussions of energy security, gains paramount importance in a new world of interconnected systems. Rapidly growing demand, particularly in Africa and Asia, also has geopolitical implications that make themselves felt in global energy markets, trade patterns and strategic alliances. Addressing these considerations is key to ensuring a responsive and resilient energy framework, one adaptable to both gradual shifts and sudden changes. In a broader sense, managing and moderating demand growth through energy efficiency and demand response policies and investments can mitigate competition for energy resources and market access.

Climate change impacts and extreme weather effects must become an integral part of energy security considerations, including infrastructure, trade and demand response measures. Essential steps include rethinking the location and design of energy assets and infrastructure to enhance resilience, implementing robust construction methods, and formulating contingency plans for extreme weather events. Enhancing early warning systems and emergency response strategies are also vital for tempering the impact of extreme weather events on energy supply chains. Adaptation responses across sectors should leverage renewable energy to provide cost-efficient, integrated, and reliable solutions for climate adaptation and energy systems resilience.

Traditional threats to energy systems, such as physical attacks on infrastructure and disruptions due to conflict or strategic manipulation, remain critical concerns for energy security. However, the scope of risk will reduce geographically, as electricity is delivered in real time, and consumption will continue to be predominantly domestic. Conversely, the increasing prevalence of hybrid threats that combine physical and cyber elements creates a multi-faceted risk landscape. Cascade effects through interconnected electricity systems can trigger physical disruptions across countries. Building resilience against such multi-faceted threats is a strategic necessity.

Cybersecurity will grow in importance in electrified and digitalised systems. As energy systems become even more complex and digital technologies even more indispensable, the range of potential threats and the diversity of actors capable of compromising these systems also grow. The critical nature of energy systems implies that any significant threat can have consequences extending far beyond the energy sector. Therefore, it is imperative to develop advanced, agile, and comprehensive strategies to manage risk and rapidly adapt to the evolving threat landscape.

Human security must become an integral dimension of energy security. Threats such as population displacement, poverty, instability and inequality amplify one another; together they can undermine peace and increase geopolitical instability. Renewables-based transitions offer many opportunities for improving human security, although attention must be paid to issues such as resource competition, especially as climate effects increase.

© JossK; shutterstock

© coldsnowstorm; iStock

CHAPTER 1

A NEW ERA FOR ENERGY SECURITY

The transition to renewable energy promises to change the dynamics of energy trade, alter the patterns of international dependency and reshape the geopolitical landscape. This impending shift underscores the need to take a systemic approach to energy policy – one that assimilates the distinct characteristics of a landscape dominated by renewables and marked by expanding electrification, digitalisation and decentralisation.

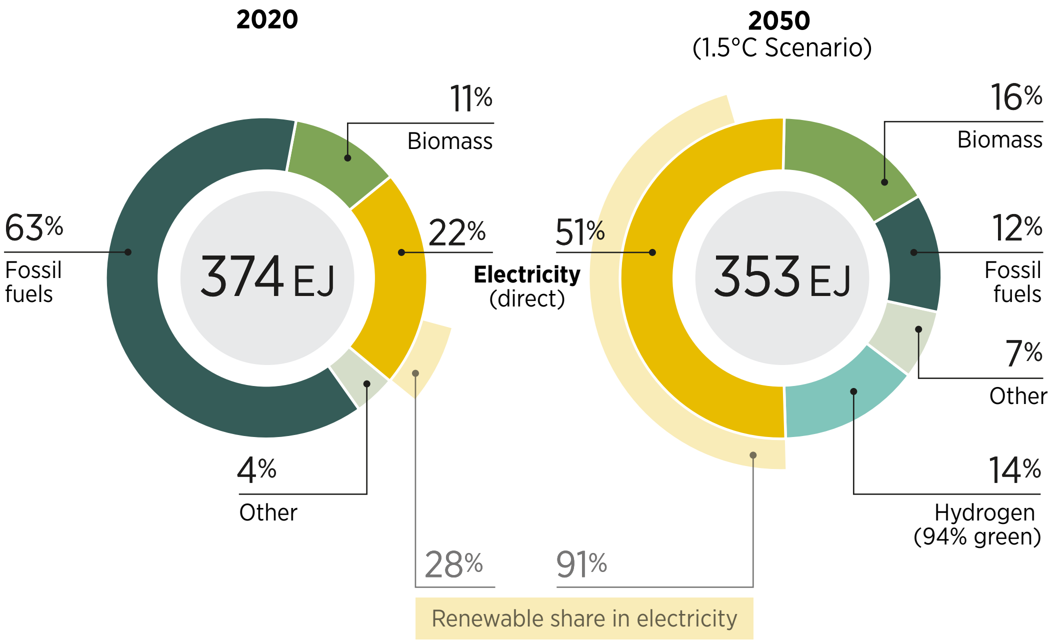
Traditional approaches to energy security are already proving insufficient. The evolving energy system calls for a proactive strategy to shape interdependencies and bolster the resilience of the energy system, enabling it to adapt not only to changes within the energy sector but also to wider economic, social and political shifts. Such a strategy implies the incorporation of diverse elements into policy making, including technological innovation, environmental concerns, economic trends and social implications. Fundamentally, addressing energy security in the age of renewables requires accommodation of every country's needs in a process steered by principles of fairness and human security.

The goal of this report is to offer policy makers insights into evolving energy security considerations, thereby helping them to fashion robust, forward-looking energy security strategies that will promote climate neutrality, global equity and responsible stewardship of ecosystems. By revisiting traditional approaches to energy security and identifying overlooked areas and emerging factors, the report equips policy makers with a more comprehensive understanding of energy security in renewables-dominated systems.

In the first chapter, the report explores the geopolitical dimensions of energy security and key differences between energy systems dominated by different fuels. The second chapter examines the effects of a renewables-based energy system on trade and power relations. The third chapter outlines a refined perspective on energy security, mapping out its multi-dimensional nature.

The report is guided by IRENA's *World Energy Transitions Outlook*, which defines an energy transition pathway consistent with the agency's 1.5°C Scenario. Under the scenario, the share of renewable energy in the global energy mix would increase from 16% in 2020 to 77% by 2050. Total primary energy supply would remain stable due to increased energy efficiency and growth of renewables. Renewables would increase across all end-use sectors, though a high rate of renewables-based electrification in sectors such as transport and buildings would require a twelve-fold increase in capacity by 2050, compared to 2020 levels.

FIGURE 1.1 Total final energy consumption by energy carrier according to IRENA's 1.5°C Scenario, 2020 and 2050



Source: (IRENA,2023b).
Note: EJ = exajoule.

1.1 THE GLOBAL SHIFTS AFFECTING ENERGY SECURITY

The energy system has undergone profound shifts over time, but the thinking around energy security has remained deeply connected with the supply of fossil fuels. In recent years, energy security has surged in prominence, largely due to the volatility of fossil fuel markets, the ripple effects of the COVID-19 pandemic and the competitiveness of renewable energy. These developments have occurred against the backdrop of three global shifts, each poised to critically influence the future of energy security.

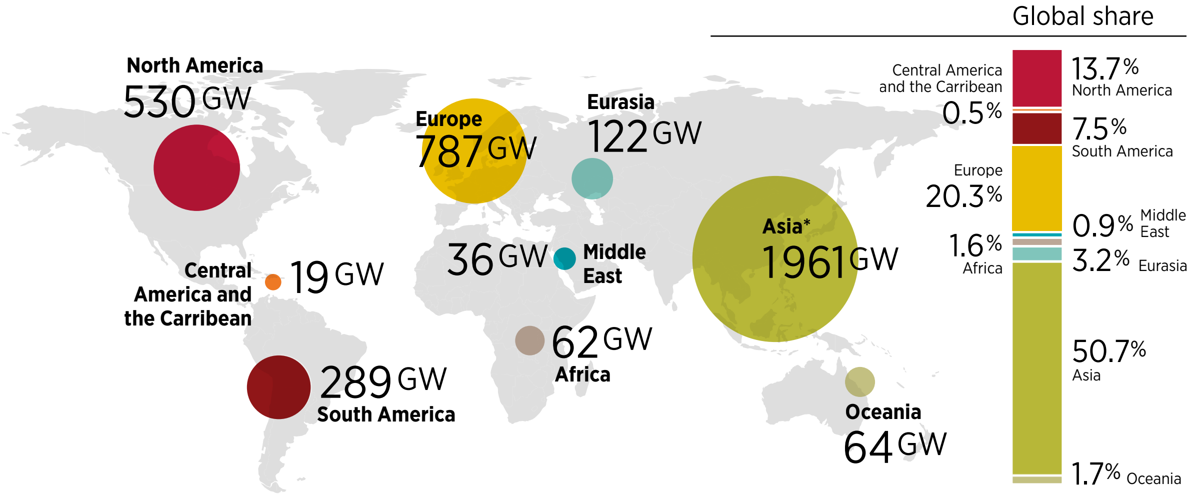
First, **major geopolitical shifts** are underway. The social and economic aftermath of the pandemic has had major effects on global trade, leading to heightened protectionist measures in some nations. Increased incidents of conflict between and within countries, sanctions, and supply chain disruptions have directly and indirectly affected the energy sector. Examples include rising transition technology prices and a growing focus on the vulnerabilities. Power competition between states and regions is spilling over into markets for clean technologies and critical minerals. In addition, events such as the attacks on the Nordstream pipelines in the Baltic Sea and disruptions in the supply of oil and liquefied natural gas through the Red Sea underline the links between energy security and military matters. This new environment has heightened concerns about foreign dependency and altered partnerships and alliances.

Second, the **global energy transition** is accelerating. The rise of renewable technologies, notably wind and solar power (which are developing faster than any fuel in history), has moved renewables from the margins to the centre of the global energy system. Energy systems are becoming electrified, digitalised and interconnected, with a deep impact on energy security. The renewable energy conversation, once dominated by concerns about the costs of technology and the challenges of integration, now positions renewables as a major part of energy sovereignty and security for many nations.

In 2023 alone, some 473 gigawatts (GW) of new renewable power were installed, bringing the global total to almost 4000 GW. Moreover, COP28's call for a transition away from fossil fuels, while tripling renewables and doubling efficiency by 2030, is likely to further accelerate the transition. The rise of renewables is already reducing the need for imports of fossil fuels for some countries, but broad-based reliance on fossil fuels will remain in the coming decades. In the meantime, the process of transitioning away from the fossil fuel-based system is likely to bring more price volatility and market uncertainty. At the same time, policy making is becoming more complex, blending energy strategies with the imperative of a just transition and wider socio-economic effects.

© Jacques Tarnero; shutterstock

FIGURE 1.2 Renewable power capacity by region, 2023



Source: IRENA (2024b).

Notes: *China accounts for 1 457 GW; GW = gigawatts.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

It is also noteworthy that renewable energy deployment patterns are persistently concentrated in a few regions and around a limited range of technologies. These patterns are accompanied by two trajectories: 1) growing inequality, with wealthier nations moving forward rapidly and leaving the poorer ones behind (Figure 1.2); and 2) insufficient systemic investment in infrastructure, policy, institutions and people (IRENA, 2024b).

At the same time, a new set of interdependencies is emerging. Trade patterns for imported fuels and carriers, such as clean hydrogen, are ushering in new diplomatic relations (IRENA, 2022a), as is the push for diversification of metal and mineral value chains (IRENA, 2023a). With the quickening pace of electrification of energy systems, interconnectors and cross border trade will grow in importance. Coupled with the reliance on new energy carriers, such as green hydrogen, energy trade may become more regionalised (IRENA, 2022a). Overall, these systemic shifts signify that energy infrastructure, technologies and their value chains are gaining new strategic relevance.

Thirdly, the physical effects of **climate change** on energy systems and supply chains are increasing year by year. They are already affecting supply, distribution and demand for energy. Historically, climate change and energy security have seldom been discussed together. Now, however, the risks posed to energy infrastructure by more frequent extreme weather events, especially storms and droughts, make the combination impossible to ignore. For instance, the Texas gas pipeline freeze in early 2024 led to a decrease in natural gas output (Scott, 2024), following even more severe instances in February 2021 and December 2022. The historic flooding in Pakistan in 2022 submerged a third of the country and led to cascading failures of energy infrastructure. The Panama Canal is experiencing one of its most severe droughts in decades, significantly affecting global shipping and trade, including trade in energy commodities (UNCTAD, 2024). Simultaneously, climate change's effects on demand amplify supply risks. The California power grid, for example, faced major challenges in 2022, when heat-induced demand for cooling coincided with grid strain from extreme temperatures.

All parts of the world face challenges due to extreme weather conditions, serving as a reminder of the increasing vulnerability of energy infrastructure and global supply chains to climate change. Despite political pressure to stay on the 1.5°C trajectory, trends clearly show the energy transition to be off track (WHO *et al.*, 2023). This makes climate change all the more relevant to discussions on energy security as it is emerging as a new layer of risk.


© ungvar; shutterstock

1.2 RETHINKING ENERGY SECURITY

Historically, the approach to energy security has remained largely static, without a universally accepted definition. During the 20th century, especially in the wake of World War II, reliable supplies of fossil fuels emerged as a key priority for the economies of developed nations. With oil resources concentrated in a limited number of countries, the issue became an essential part of diplomatic and trade relations, enmeshing energy security with geopolitics.

The geopolitical turbulence of the 1970s turned the price of oil into a serious economic question for importing nations (Paust and Blaustein, 1974). The period triggered the creation of frameworks for the assessment of energy security that focused chiefly on national import dependency, supply concentration and infrastructure capacity (Cherp and Jewell, 2013). This period also forged the link between energy security and unhindered access to affordable oil, a link that endures to this day.

The flavour of the period is evident in the creation of the International Energy Agency (IEA) as an importing nations' security club, as well as the establishment of national strategic petroleum reserves in developed nations. The IEA defined energy security as the uninterrupted availability of energy sources at an affordable price, a definition that has guided its members' policy making since the 1970s.

© JudiLen; iStock

© carterdayne; iStock

The 1970s oil crisis prompted the rethinking of national energy strategies. France focused on developing nuclear power, while Denmark and Brazil started investing in renewable energy. Over time, as the rapid industrialisation of emerging markets intensified competition for oil, natural gas gained strategic importance. Coupled with the growing focus on climate change, the pressure to diversify both fuels and producers intensified.

The energy crisis of 2022 marked a turning point in the global energy discourse. In the wake of the COVID-19 pandemic, as governments sought to stimulate economic recovery, energy demand surged. At the same time, other challenges emerged, encompassing supply chain disruptions, geopolitical tensions, and changes in energy policy, exacerbated by the lasting effects of the pandemic. The intentional disruption in energy trade between Europe and Russia immediately prior and since the beginning of the war in Ukraine placed immense strain on Europe's energy sector. Compounding this problem, the fluctuating availability of nuclear power in France and severe droughts that reduced hydropower output in Europe, left the European Union with a shortage of approximately 7% of its low-cost electricity supplies in 2022 (Zachmann, 2023).

Fuel shortages, competition for limited resources, inflation, rising food costs and increased living expenses worldwide have rippled through sectors and geographies, suppressing or even reversing previous advances and widening the gap between haves and have-nots. The fragility of economies reliant on imported fossil fuels was exposed, along with the political and social consequences that energy insecurity brings. Once again, the rethinking of energy strategies took centre-stage in many countries and regions. Attention turned to renewable energy as an avenue toward resilience, energy independence and sovereign control.

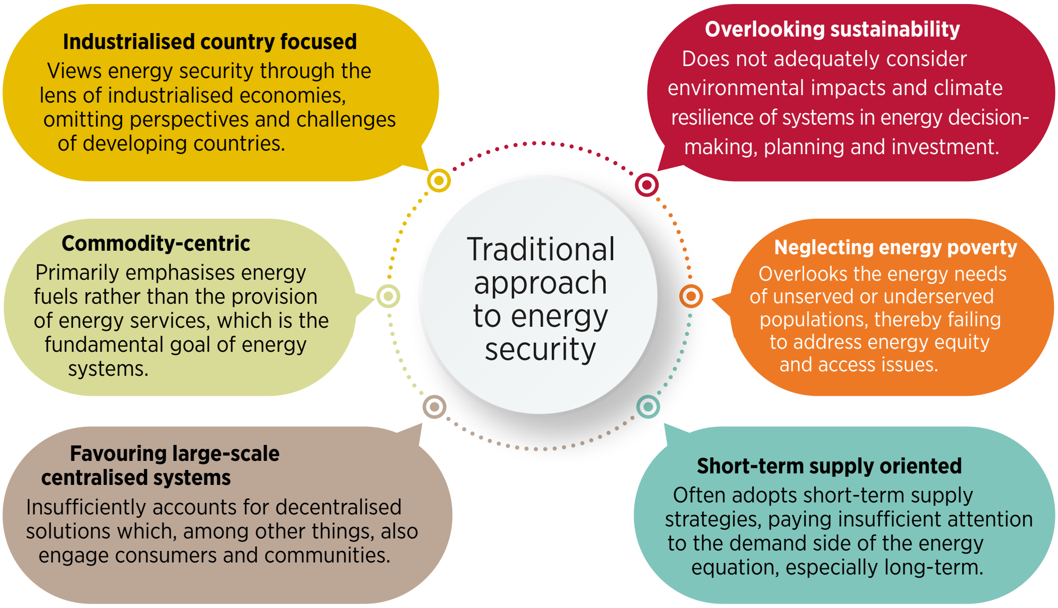
With energy security traditionally framed around the interests of countries with high energy use, energy crises in developing countries have not been extensively analysed. For instance, occurrences such as the 1980s fuelwood crisis have not featured in discussions of energy security. It was estimated that some 1 billion people lacked enough fuelwood to meet their needs. The situation was particularly acute in Asia, where over 700 million people were affected with severe social, economic and ecological consequences (FAO, 1997).

That 675 million of the world's people still lack access to electricity and 2.3 billion lack access to clean cooking (IEA *et al.*, 2023) reflects persistent energy poverty with wide ranging social, economic and geopolitical implications. The situation underscores the need for a new, universal energy security framework that reflects the needs of both developed and developing nations.

The concept of renewables influencing energy security is a relatively recent development, previously overshadowed by climate considerations as the primary driver of their deployment. The Paris Agreement on Climate Change in 2015 was a watershed moment that positioned the decarbonisation of the global energy system by 2050 at the centre of climate action. Renewable energy, already emerging as increasingly competitive with fossil fuels, became synonymous with preservation of the earth's climate. In parallel, the membership of the nascent International Renewable Energy Agency grew rapidly. Established only four years before the Paris conference, IRENA's mandate to promote the widespread adoption of all sources of renewable energy captured the attention of developed and developing countries alike (IRENA, 2009). In 2023, the outcome of COP28 firmly positioned renewable technologies, along with efficiency, as essential to decarbonisation through 2030.

The implications of the growing role of renewables in energy security are substantial, especially considering that renewable power capacity needs to grow to 11 terawatts by 2030 to stay on a climate-safe pathway. The traditional approach to energy security, which, as noted, hinges on the availability and affordability of fuel supplies, has several key limitations in the era of renewables (Figure 1.3).

FIGURE 1.3 Traditional approach to energy security



These limitations highlight the need for a more holistic and forward-thinking approach to energy security, one that integrates energy services, sustainability and equity. Policy priorities related to ensuring energy security therefore need to evolve from a narrow focus on security of physical supply to a multi-dimensional set of considerations and options, as discussed in Chapter 3. Critically, energy security in the era of renewables must account for the needs of all countries, guided by the principles of equity and human security (United Nations, 2012).

If handled properly, the transition to renewables-dominated energy systems can mitigate key risks associated with oil and gas dependency and vulnerabilities. Harnessing national and regional energy solutions based on renewables alters the dynamics of dependency, offering nations a greater degree of energy independence. While geopolitical factors – such as market manipulation, chokepoints, and infrastructure disruptions – remain relevant, their impacts are expected to be less severe in a renewable energy landscape. For instance, the move towards electrification and a higher share of renewable energy can reduce risks associated with weaponisation of fuels, market manipulation, interruptions in long-distance supply chains and environmental disasters (*e.g.* oil spills). With the right policies, generating renewable energy locally optimises costs and offers substantial socio-economic and welfare benefits, aligning energy production more closely with local needs and capabilities. It is important to note, however, that social acceptance and community participation play a major role in this context, which may affect the speed of the transition.

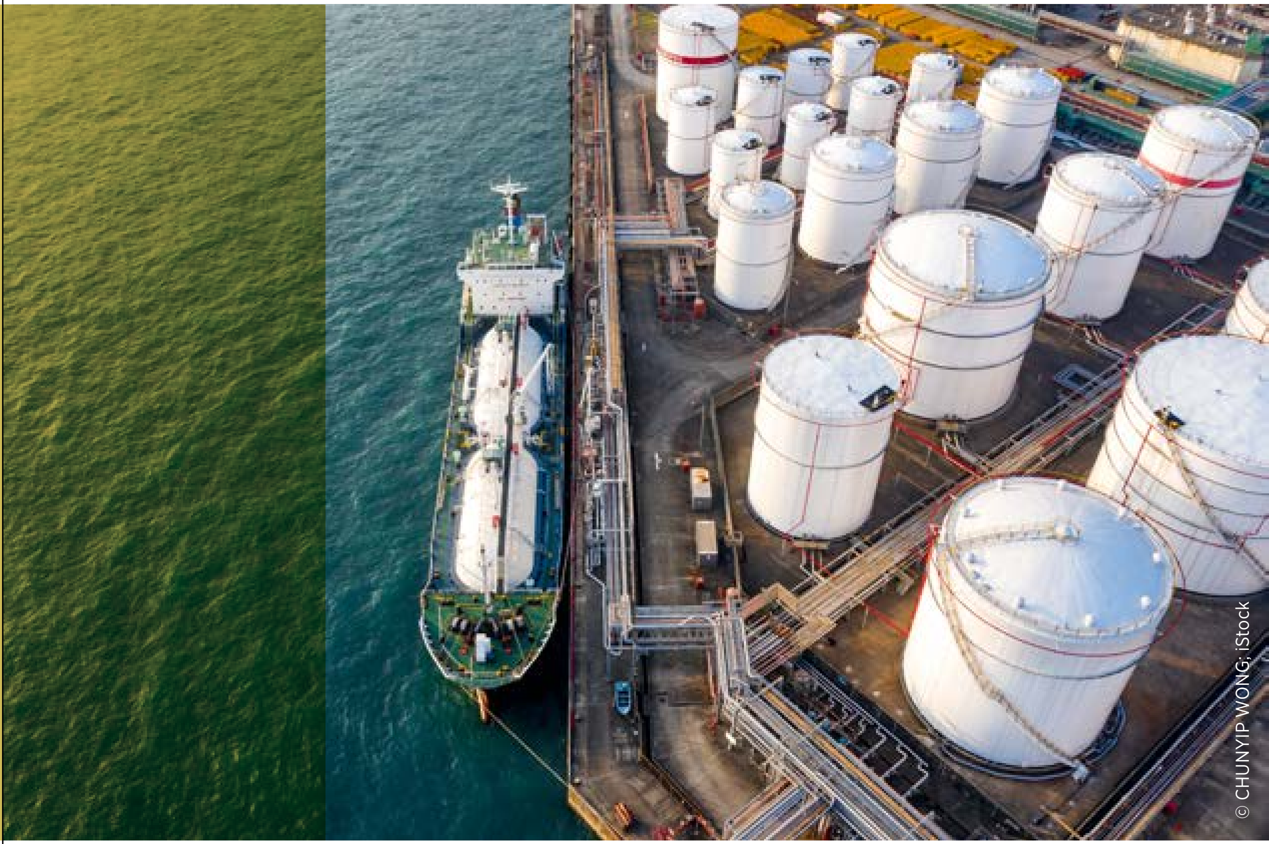
In the shift towards renewables-dominated energy systems, new considerations must be addressed if energy security is to be ensured. Given the abundance of renewable energy sources and their competitiveness, supply factors alone will decline in importance. Priority will be placed on a broader range of factors, including those noted below.

© Andrewshots; shutterstock

- **Modernisation and expansion of infrastructure:** The transition will necessitate expansion and new types of infrastructure like hydrogen pipelines, storage solutions and transport mechanisms, many of which will need to be built from the ground up.
- **Flexibility:** In transitioning to renewable energy, the focus shifts to system flexibility and key solutions like digitalisation, "power to X", advanced batteries and storage technologies, as well as energy efficiency, demand management and consumption response. Stability of the electrical grid and the development of networks for cross-border trade become crucial.
- **Availability of and access to technology:** In a renewables-dominated system, energy security is heavily influenced by the availability and accessibility of technology, emphasising the need for robust supply chains (for technology and inputs like materials) and equitable distribution.
- **Economic and trade considerations:** The cost of capital, especially in developing countries, and the implications of emerging carbon trade levies and similar mechanisms add nuance and complexity to the geopolitics of energy security.
- **Strengthening resilience:** Considerations of climate, ecosystems and human security become integral to energy security assessments.
- **Decentralisation:** Opportunities grow for the use of indigenous resources and the potential involvement of citizens and smaller businesses in the energy system.

In this new landscape, energy security dependencies will still exist – but they will be based on different foundations. Energy security options will be more diverse, but the energy system may become more complex given the array of technologies and participants, necessitating proactive and anticipatory policy making. To fully harness the benefits of renewable energy systems while mitigating associated risks, policy makers must design robust, resilient, adaptable and secure energy systems. The decisions made today will have lasting effects, owing to the long lead times and lifespan of energy infrastructure and technologies. Such choices are particularly critical for developing countries striving to expand energy access while driving development and industrialisation, given the opportunities along renewable energy value chains and in clean manufacturing.

© Stefan Dinse; iStock



© CHUNYIP WONG; iStock

© deyanarobova; iStock

CHAPTER 2

TRADE, SECURITY AND INTERDEPENDENCE

HIGHLIGHTS

- In the global transition to renewables and low-carbon technologies, it is imperative that countries avoid inadvertently creating new security risks.
- By traditional energy security standards, renewables are superior to fossil fuels, as they tap into affordable and abundant flows of energy (such as solar, wind, hydro and geothermal energy), which cannot easily be disrupted for geopolitical purposes.
- The shift toward renewable energy and clean energy technologies is poised to foster greater self-sufficiency among countries. Energy dependencies in a net-zero world will be more regional and less global. At the same time, countries will continue to be interconnected through global clean technology supply chains.
- During the energy transition, residual dependencies around fossil and nuclear fuels will remain. At the same time, new dependencies will emerge around increased trade in electricity, hydrogen, critical materials and clean technologies. These new dependencies are markedly different from the conventional dependencies surrounding fossil fuels. Dependence on oil is very different from dependence on imported solar PV panels. A disruption in the latter may lead to a delay in the deployment of new solar panels, but it will not affect the functioning of those already installed.
- Similarly, since electrons can flow both ways, it is best to think about electricity trade as creating interdependencies, rather than the asymmetric dependencies that are well-known in oil and gas relationships. Yet shared grids also create shared risks, directing attention to the ownership and security of energy infrastructure, access to and control of that infrastructure, and back-up options in case of disruption.
- Unlike crude oil and natural gas, hydrogen is a manufactured product that can be made in many locations. Notably, green hydrogen production will be much more dispersed than oil and gas production, making it less sensitive to political manipulation.
- Critical materials must be mined, but unlike fossil fuels a disruption in their supply does not result in immediate energy shortages or price spikes. Moreover, over the medium to long term they can be recycled and in many cases also substituted thanks to innovation.
- Nonetheless, high concentrations in the supply chains of clean energy technologies – particularly critical materials, solar PV and batteries – must be addressed.

This chapter delves into the trade-related aspects of energy security.[1] While most attention is devoted to imports, given the focus on energy security, both sellers and buyers derive benefits from trade and thus depend on it, although their interdependencies may or may not be symmetrical. In general terms, the shift towards electrification and renewables moves us from the asymmetrical bilateral dependencies typical of fossil fuel relationships to more symmetrical trade relations, forming a complex network of interdependencies that reshape the geopolitical landscape. In this new renewable era, nations face new trade risks and vulnerabilities, prompting the need for innovative energy security strategies.

"Trading one dependency for another" is often heard in discussions about the geopolitics of the energy transition. However, the phrase can be misleading. The geopolitics of renewables differ substantially from those of oil and gas. Trade in renewable technologies, electricity and hydrogen is less susceptible to acute shortages or cartelisation, fostering a more equitable trade environment. Although certain transition commodities, like rare earths or other critical minerals, may potentially be weaponised, the effect of such a disruption would be limited. It may slow down the deployment of clean energy technologies, but it is unlikely to cripple entire energy systems.

Shifting to renewable energy significantly reduces the risk of disruptions in energy supply. In highly electrified economies, the focus shifts from fuel supply to service provision and from securing critical energy assets abroad to securing them at home. In this changing landscape, several key factors are paramount in shaping trade relations. These include access to technology, intellectual property rights, manufacturing and innovation capabilities, the availability of skilled labour, and the capital required to undertake decarbonisation and electrification efforts. All of these factors will shape the evolving patterns of energy trade and security.

The world is embarking on a journey that will span at least two transitional decades before reaching the envisioned net-zero future. Policy makers are thus faced with the task of securing energy while transitioning away from fossil fuels. This challenge is compounded by the incomplete development of grids, hydrogen markets, green industries and other necessary elements for achieving net-zero emissions. Further investments in fossil fuel infrastructure may prove necessary in some cases, but because they risk perpetuating emissions and energy insecurities such investments should be avoided where possible. Unlike fossil fuels, renewables typically foster energy security, autonomy, flexibility and sustainability.


© Eliane29; iStock

---

[1] *We deal with other aspects of energy security (e.g. how to design systems so they can absorb high volumes of intermittent renewables) in Chapter 3.*

2.1 THE ENERGY SECURITY RISKS OF RENEWABLES VS. FOSSIL FUELS

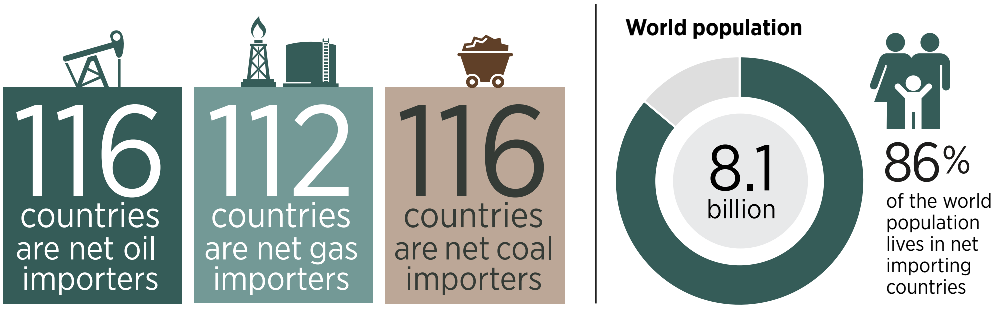
To achieve the Paris climate goals, the world's energy mix will need to undergo profound changes. Under IRENA's 1.5°C scenario, the share of fossil fuels would diminish dramatically – from 63% of total final energy consumption in 2020 to only 12% in 2050 (Figure 1.1). Electricity would become the main energy carrier, with its share rising from 22% today to more than half in 2050. Biomass and hydrogen (most of which will be based on renewables) would both command larger shares of final consumption in 2050 than fossil fuels. There is no doubt that realising this scenario is a monumental challenge, of a scale and scope unlike any other energy shift in history.

The evolving energy mix will significantly affect energy trade dynamics, international interdependencies and broader geopolitical relations. For a considerable number of nations, fossil fuels, notably oil and gas, represent a substantial import dependency and, in certain instances, a source of strategic vulnerability. In the global transition to renewables and low-carbon technologies, countries must not inadvertently create new energy security risks.

Fossil fuels have fuelled economic growth and industrialisation over the past 150 years, but their environmental impacts, coupled with geopolitical vulnerabilities and geographic concentration, have underscored the need to transition away from these fuels, as confirmed by COP28. By traditional energy security standards, renewable energy offers the potential for greater stability and resilience owing to their abundance and wide availability, thus reducing overall vulnerability to energy supply disruptions (see Box 2.1).

Fossil fuel reserves are concentrated in a limited number of countries; for most countries, fossil fuels must be imported, weighing on the importer's balance of trade and geostrategic autonomy. Petroleum is the top import product by value in no fewer than 128 countries (Wright, 2023). The majority of countries are net fossil fuel importers and some 8.1 billion people – that is, 86% of the world population – live in countries that are net fossil fuel importers (see Figure 2.1). The supply of fossil fuels has historically been influenced by geopolitical factors, with centralised infrastructure vulnerable to disruption and prices exhibiting high volatility.

FIGURE 2.1 Share of countries and global population dependent on net imports of fossil fuels



Source: (UN Comtrade Database, 2022).

BOX 2.1 Comparing energy security risks for fossil fuels and renewables

ENERGY SECURITY RISK	FOSSIL FUELS	RENEWABLES
Resource availability	Finite resources, subject to depletion (stocks).	Abundant resources, subject to variability (flows).
Resource concentration	Concentrated in specific regions or countries, subject to geopolitical control.	More evenly distributed globally, although access to the resource depends on technologies (*e.g.* solar PV panels) and materials (*e.g.* lithium) whose manufacture and sourcing are concentrated.
Vulnerability to supply disruption	Vulnerable to supply cutoffs caused by physical disruptions or geopolitical tensions, thus creating immediate energy shortages and/or price spikes.	Resources themselves (*e.g.* wind, water, sun) are inherently available and distributed. While the broader supply chains behind renewable technologies and materials are vulnerable to cut-offs, these do not pose immediate risks to energy supply.
Infrastructure resilience	Vulnerable to significant disruptions due to centralised infrastructure. Burning fossil fuels creates a negative feedback loop of climate impacts on energy systems, exacerbating vulnerabilities.	Decentralised infrastructure increases resilience to disruptions.
Affordability	Susceptible to price fluctuations and market volatility.	No fuel costs, but sizeable up-front costs and system costs (*e.g.* grid reinforcement). Declining costs of renewable technologies enhance affordability over time.

© Nikada; iStock


© georgeclerk; iStock


© Chris Gordon; iStock

In contrast, renewable energy sources are widely available across many countries and are generally less susceptible to geopolitical control and manipulation, even though concerns persist regarding the global distribution and accessibility of low-carbon technologies. The fossil fuel crisis of 2022 was a telling reminder of the powerful economic benefits that renewable power can provide in terms of energy security. In 2022, the renewable power deployed globally since 2000 saved an estimated USD 521 billion in fuel costs in the electricity sector (IRENA, 2023b).

The fossil fuel energy system comprises hundreds of millions of workers and some of the world's biggest companies; it also contributes significantly to global GDP. Oil stands out. Before the outbreak of the pandemic, approximately USD 2 billion of petroleum was traded each day worldwide, making oil the largest single item in the balance of payments and exchanges between nations. Control over energy resources and supply lines has been a currency of power, and lack of such control has been a source of geostrategic vulnerability. Some states have sought to weaponise energy interdependence and use it as a foreign policy tool (Van de Graaf and Sovacool, 2020).

While the supply of coal, oil and gas can be disrupted, renewable energy sources remain impervious to such interruptions. It is impossible for a particular country to deprive another of wind, solar, tidal, wave or geothermal energy.[2] As former US President Jimmy Carter said in 1979, "No one can ever embargo the sun or interrupt its delivery to us." While the resources themselves (*e.g.* solar irradiation or wind) remain impervious to geopolitically motivated interruptions, access to these renewable resources depends on technology, which may prove prohibitively costly and inaccessible for certain developing and emerging economies. Thus, there is a pressing need to facilitate technology transfers and ensure equitable access to intellectual property rights to encourage widespread deployment and promote equitable and sustainable development pathways.

As the global energy landscape shifts towards renewable sources, energy geopolitics will continue to play a role, albeit with diminishing prominence. The bilateral dependencies that have historically defined the hydrocarbon trade, influencing foreign policy in both importing and exporting nations, are set to transform into a more balanced paradigm of interdependency. This evolution towards a renewable-centric energy system will reshape the dynamics of dependencies, altering the traditional supply-demand framework of energy trade.

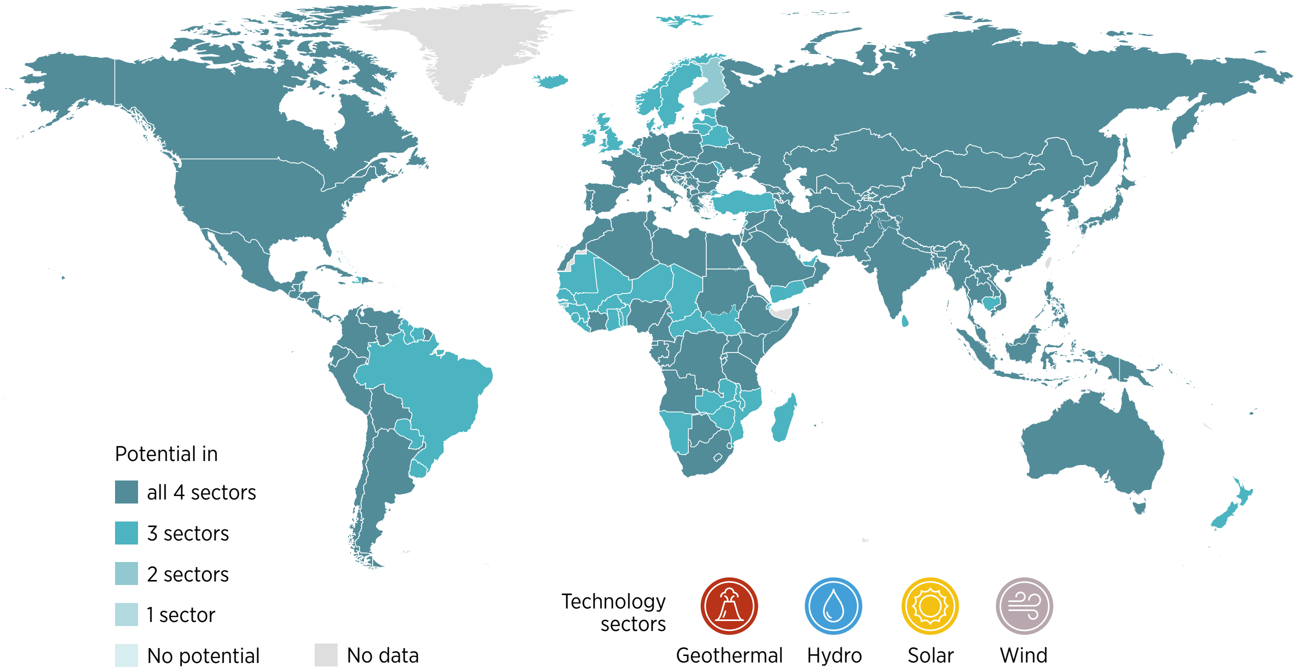
[2] *Hydropower may be an exception. Hydropower dams carry the potential for competition between upstream and downstream countries over shared water resources. Disputes over water rights and allocations have escalated into geopolitical conflicts in several regions over time.*

2.2 ENERGY RELATIONS IN A NET-ZERO WORLD: MORE REGIONAL, LESS GLOBAL

Shipments of fossil fuels extracted on a vast scale from the subsoils of a few countries fostered the globalisation of energy markets. For many countries the supply of energy became entangled with faraway locations and events. At the same time, energy diplomacy became a standard fixture of many countries' foreign policies.

The shift towards renewable energy and other clean energy technologies is poised to change that by fostering greater self-sufficiency among countries. Figure 2.2 shows that most countries in the world have access to multiple forms of renewable energy, in contrast to the concentrated reserves of fossil fuels. As countries harness their domestic renewable potential (whether in solar, wind, hydro, marine, biomass or geothermal) (IRENA, 2009) they will become less reliant on internationally traded fossil fuels. And although a decarbonised world will still require extensive supply chains for clean energy materials, components and products, the globalisation of energy trade itself is likely to diminish (Bordoff and O'Sullivan, 2021).

FIGURE 2.2 Techno-economical potential of geothermal, hydro, solar and wind

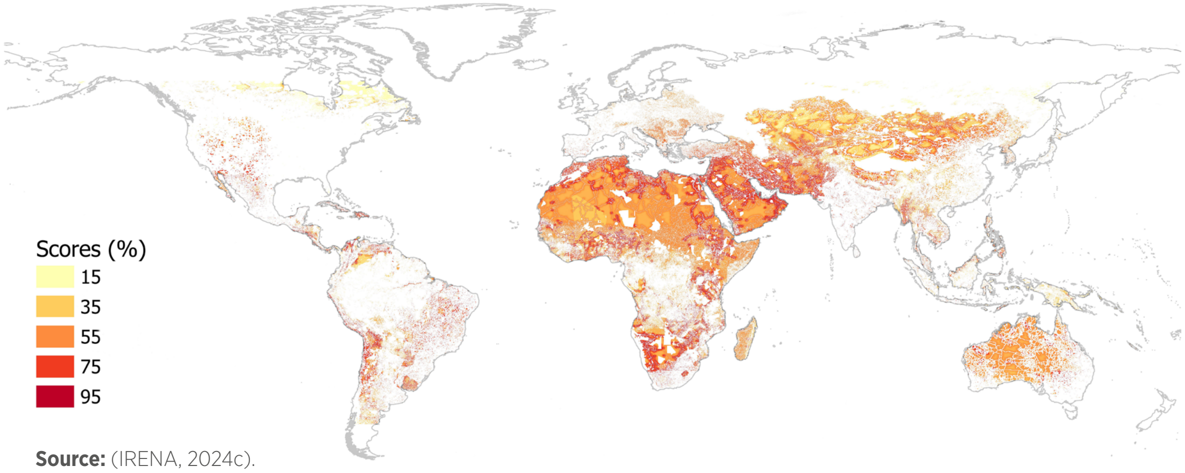


Source: (IRENA, 2024a).

Notes: Figure is based on IRENA Global Atlas datasets. Only geothermal, hydro, solar and wind sources are included. Data for calculating the techno-economic potential of bioenergy and marine sources is currently unavailable.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

FIGURE 2.3 Suitable area for utility scale solar

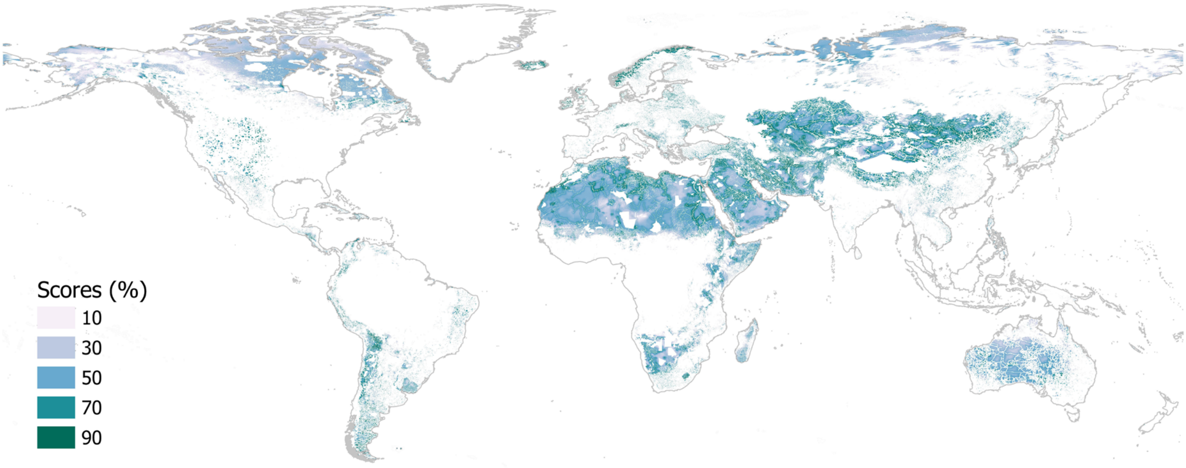


Source: (IRENA, 2024c).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Notes: The scores express the suitability of areas to develop solar PV and wind projects, with the scale of 0–100% corresponding to the worst and best areas, respectively. Suitable areas exhibit high resource potential and low technical, financial and socio-environmental impacts.

FIGURE 2.4 Suitable area for wind



Source: (IRENA, 2024c).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

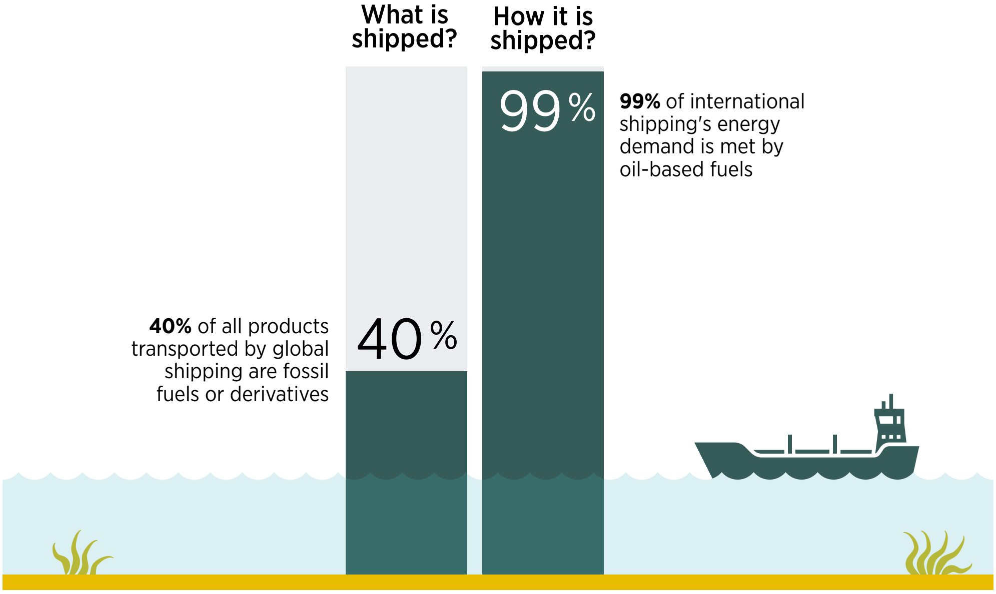
Notes: The scores express the suitability of areas to develop solar PV and wind projects, with the scale of 0–100% corresponding to the worst and best areas, respectively. Suitable areas exhibit high resource potential and low technical, financial and socio-environmental impacts.

The transition away from fossil fuels may also result in less seaborne energy trade, as some 40% of maritime cargo today is made up of fossil fuels or derivatives (Subramanian, 2022) (Figure 2.5). Studies have found that fossil fuel trade would decrease significantly by 2050 in a 2°C world, and that the decline would be unlikely to be compensated by an increase in bioenergy trade (Sharmina *et al.*, 2017). That said, the complexity of the global shipping system makes predicting volumes and patterns of long-term future international maritime trade a challenging task (Walsh *et al.*, 2019).

Electrification of the global energy system will amplify the geopolitical and geoeconomic shift induced by renewables, given that power will be more likely to be produced locally or regionally. Unlike oil or gas, which can be transported relatively efficiently over long distances through pipelines or in tankers, transmission of electricity has long faced limitations in terms of distance and infrastructure. In 2022, only 9.37% of all electricity consumed globally was transported across borders, although the share has been rising in recent years (Ember, 2024a).

Recent advances in ultra-high-voltage transmission technology make it possible to transmit electricity over long distances (2000-3000 kilometres) with relatively low losses (Guo et al., 2022). Currently, the longest high-voltage line in the world is the Belo Monte–Rio de Janeiro link in Brazil, which connects hydropower plants in northern Brazil to major urban demand centres in southeastern Brazil, including Rio de Janeiro. The line – 2543 kilometres in length – was built by State Grid Corporation of China as part of China's Belt and Road Initiative (Power Technology, 2020).

FIGURE 2.5 Global shipping is closely intertwined with fossil fuels



Source: (UNCTAD, 2022); (IEA, 2023a).

Certain green energy molecules could also be traded. Prominent examples are clean hydrogen (or derivatives such as methanol or ammonia) and bio-based fuels and gases. However, the volumes involved are unlikely to ever match or replace current fossil fuel volumes, whether measured by volume, mass or energy content. Moreover, their trade may turn out to promote more regionalised (including repurposed natural gas pipelines), limiting the range for such trade to a couple of thousand kilometres.

The bottom line is that for trade in green hydrogen to be economically viable, the cost of production must be substantially lower in the exporting region than in the importing region so as to offset transportation costs (IRENA, 2022a). In 2022, IRENA conducted a trade assessment using a global cost-optimisation model to explore potential global trade patterns in a fully decarbonised energy system. The analysis focused on two commodities, green hydrogen and green ammonia. Findings indicate that by 2050, and under optimistic assumptions, approximately a quarter of the total global demand for hydrogen in IRENA's 1.5°C scenario could be met through international trade. The remaining three-quarters would be produced and used domestically. By 2050, around 55% of the hydrogen traded internationally would come through pipelines in the 1.5°C Scenario. The other 45% would be transported as ammonia (or other liquid). Much of this will be used as a synthetic fuel for foreign shipping or as an input for the fertiliser sector without being converted back to hydrogen (IRENA, 2022a). It should be emphasised that trade flows would be substantially lower under less optimistic assumptions and that the analysis did not consider relocation of industries, which could be an alternative to hydrogen trade and a green development opportunity for countries in the global south (IRENA, 2024b).

© Suphanat Khumsap; iStock

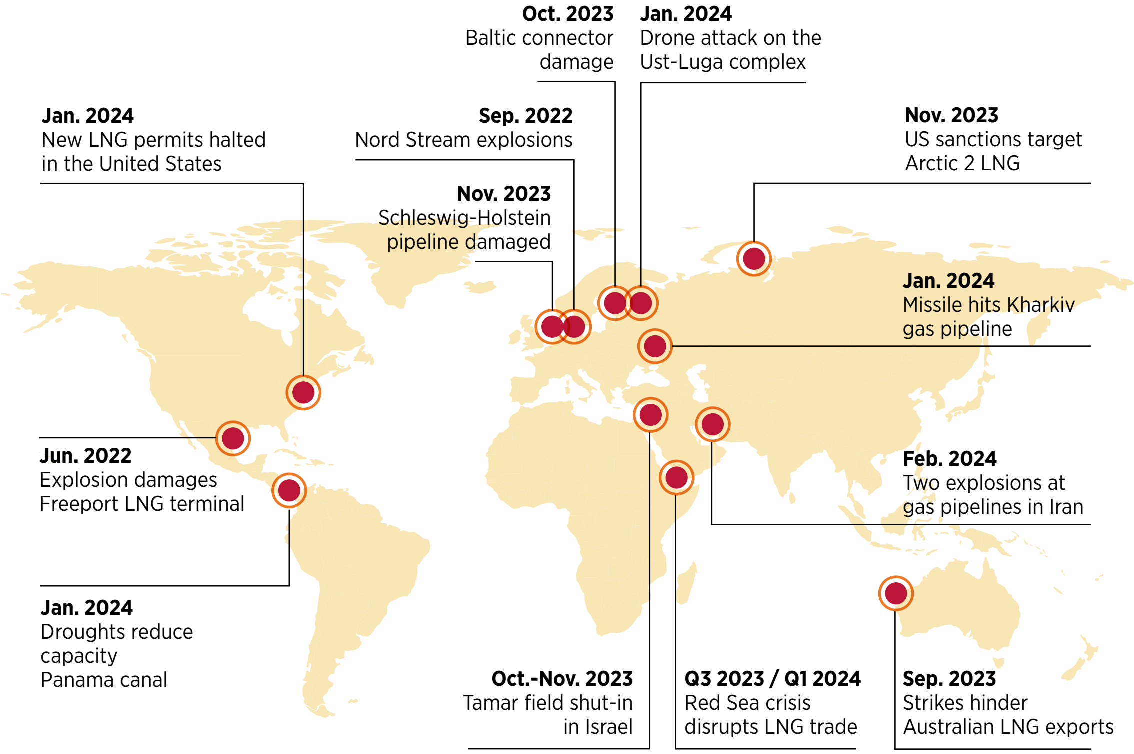
2.3 RESIDUAL FOSSIL AND NUCLEAR DEPENDENCIES

As countries decarbonise their economies and gain varying levels of energy independence, residual dependencies will persist around fossil fuels and nuclear power, and new dependencies will grow around increased trade in electricity, hydrogen, critical materials and clean technologies.

In the short term, many countries will still need to import fossil fuels; the 2022 global energy shock illustrated the risks presented by this need. Such risks will persist during the transition. Oil and gas markets remain very tense and volatile. In the last few years, natural gas markets, in particular, have been disrupted by several geopolitical events (Figure 2.6). Some 50 years after the first oil shock, oil markets also remain on edge, as shipping through the Red Sea and Suez Canal is disrupted.

Countries that have nuclear power plants, or are planning to construct them, will also remain entangled in international dependencies (Box 2.2).

FIGURE 2.6 Recent disruptions of natural gas supply



Source: Compiled by IRENA from public sources. Note that this list is just for illustrative purposes and may not be exhaustive.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

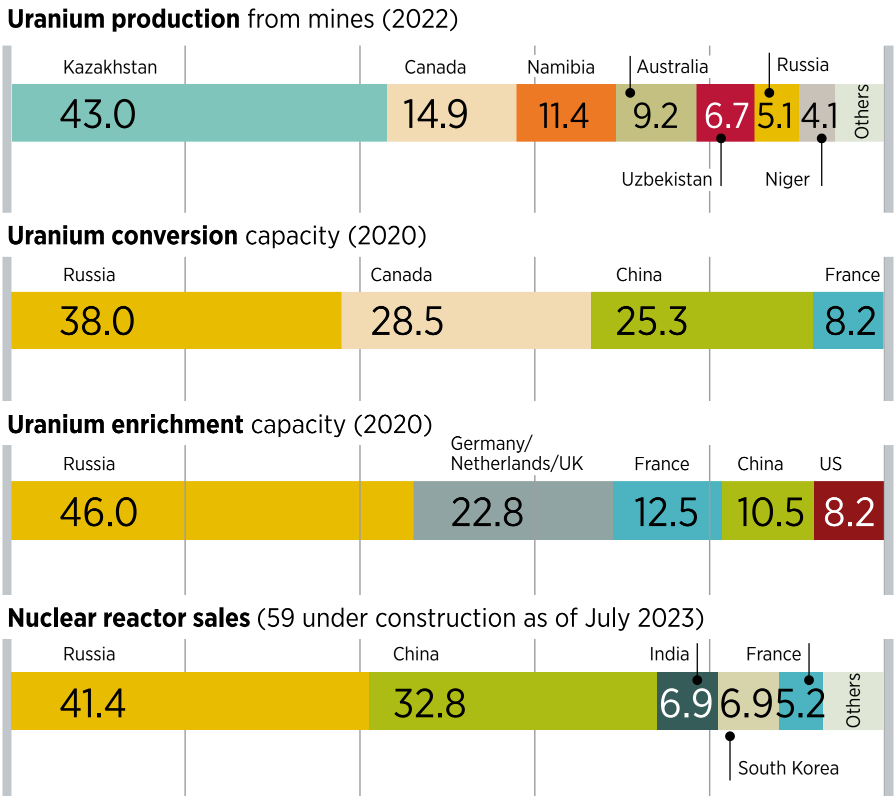
BOX 2.2 Energy security and the nuclear fuel cycle

Nuclear power plants entail their own set of international dependencies over the nuclear fuel cycle. This cycle starts with the mining of uranium and ends with the disposal of nuclear waste (IAEA, n.d).

The main raw material for today's nuclear fuel is uranium. Uranium resources are highly concentrated, with Australia (28%), Kazakhstan (13%) and Canada (10%) together holding over half of uranium resources (World Nuclear Association, 2023a). Uranium mining currently takes place in 15 countries, with Kazakhstan, Canada and Namibia being the top three producers in 2022 (Figure 2.7).

The mined uranium ore is crushed and chemically treated, often near the mining site. The result is yellow cake, a powder of uranium oxide (U_3O_8). In a next step, the powder is converted into a gas, uranium hexafluoride (UF_6), commonly known as 'hex'. In 2022, there were just four conversion plants operating commercially – in Canada, China, France and Russia. China is increasing its conversion capacity. In 2023, a mothballed conversion plant in the United States came back online.

FIGURE 2.7 Geographic concentration in the nuclear fuel cycle (percent of the global total)



Source: (World Nuclear Association, 2022 ; WNISR, 2023).

Notes: UK = United Kingdom; US = United States.

BOX 2.2 continued

An even higher level of geographic concentration is visible for uranium enrichment, the next step in the nuclear cycle. Most nuclear power plants require uranium-235 atoms enriched to a level of 3–5%: low-enriched uranium. However, there is some interest in taking enrichment levels to 7% and even close to 20% for certain advanced power reactor designs, including more than half of the small modular reactor designs now in development (World Nuclear Association, 2023b).

According to 2020 data (the latest available), enrichment capacity was concentrated in a handful of key players, with Russia accounting for the largest share – about 46% – followed by Europe (22%), the United States (8%) and China (11%) (World Nuclear Association, 2022). Together, these nations represent a surplus of worldwide enrichment capacity.

Until 2013, the conversion of military high-enriched uranium was providing about 15% of the world's nuclear fuel requirements worldwide (World Nuclear Association, 2017). Since the late 1980s, military warheads have become an important source of nuclear fuel, thanks to a series of nuclear disarmament treaties between the United States and the former Soviet Union. Under the so-called 'Megatons to Megawatts' program, from 1993, Russia converted 500 tonnes of bomb-grade high-enriched uranium into low-enriched uranium, which was purchased by the United States for use in commercial nuclear power plants. For two decades, up to 10% of the electricity produced in the United States was generated from fuel fabricated from weapons-grade uranium.

International dependencies are not limited to supplies of fuel. As of mid-2023, 59 reactors were under construction around the world, 43 of which are of Chinese and Russian design. At present, Russia is dominating the international market as a technology supplier, with 24 units under construction, 19 of which are in seven countries outside Russia (Schneider and Froggatt, 2023).

© KE ZHUANG; iStock

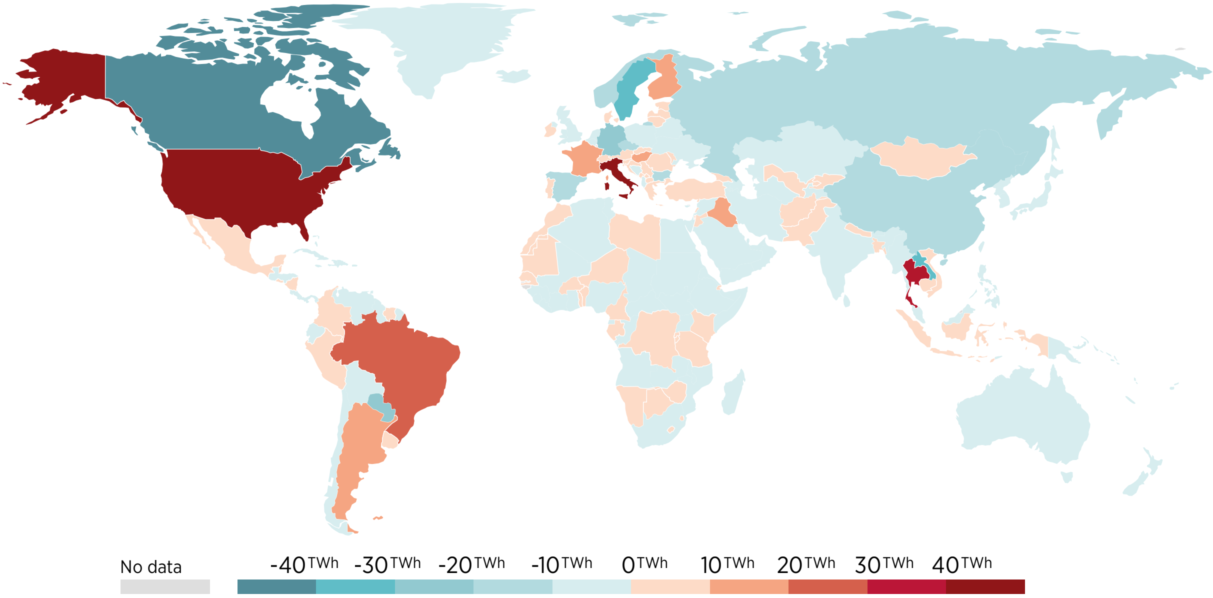
2.4 THE GEOPOLITICS OF ELECTRICITY TRADE AND CROSS-BORDER GRIDS

In most countries, electricity accounts for 20–30% of total final energy consumption, while some outliers like Iceland, Norway and Sweden have electrification rates of more than 40% (Cembalest, 2024). Growing electrification is one of the key hallmarks of the global energy transition. As a result of ongoing trends in electrification, global electricity demand will increase by almost 220% between now and 2050 (IRENA, 2023b).

Building inter-regional or cross-border transmission grids can lower the cost of making the transition. As electricity comes to satisfy a larger share of demand for energy for buildings, transportation and industry, cross-border interconnections become increasingly vital for balancing loads at optimal cost-optimisation. Continental supergrids can also help to smooth out fluctuations in supply. Studies show that the hourly profiles of wind power have low correlation over long distances – in other words, the wind is always blowing somewhere (Malvaldi *et al.*, 2017; Ren *et al.*, 2020). Moreover, the seasonal patterns of wind and solar power are complementary, so their combined supply remains somewhat constant throughout the year (Jurasz *et al.*, 2020; Weschenfelder *et al.*, 2020).

For some countries, imported electricity constitutes the bulk of electricity supply (Figure 2.8). These are usually smaller countries, such as Djibouti (90%), Luxembourg (82%), Lithuania (67%), Belize (35%) and Nepal (31%). Such high rates of import dependency can be the result of a positive choice to build out electricity connections with neighbouring countries. They could also be the result of other factors, however, such as a lack of domestic production capacity or political instability.

FIGURE 2.8 Net electricity imports (2022)



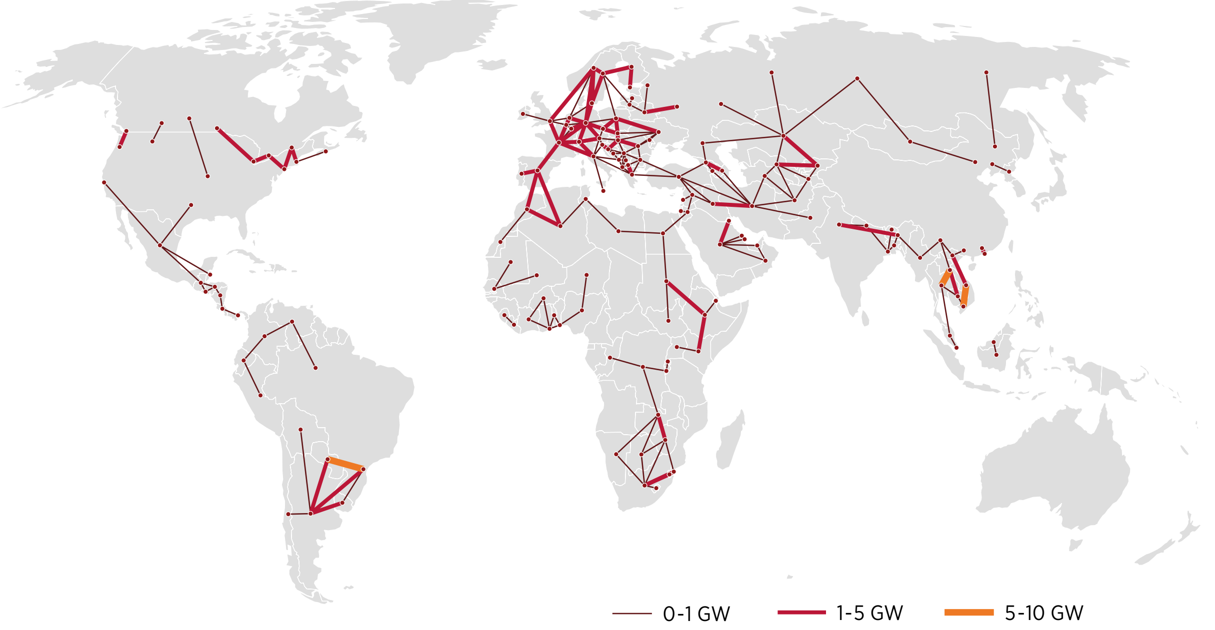
Source: (Our World in Data, 2023).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

While cross-border electricity trade creates dependencies, these differ from the dependencies of the fossil fuel world. Since electrons can flow both ways, it is best to think about electricity trade as co-dependency, rather than the asymmetrical dependency of oil and gas relationships. Even in the integrated EU electricity market, all member states, including net exporters, benefit from imports at times. During 2023, none of the 27 member countries was an exporter all of the time (ACER, 2024). Even Norway, often referred to as Europe's "green battery" due to its large hydropower reservoirs and export capacity, has been a net power importer in several years, including 2019 (0.04 TWh) and 2010 (7.55 TWh) (Ember, 2024b) Interconnectors can therefore be thought of as vectors for closer integration and co-operation. In most cases, however, political trust needs to precede the construction of cross-border energy infrastructure (Fischhendler *et al.*, 2016).

Provided that the political prerequisites are in place, one of the primary challenges in interconnecting grids is synchronisation, a task that involves aligning the frequencies of every generation facility in the connected systems. Frequency is often called the heartbeat of the electric grid. The European continental grid, for example, which supplies electricity to 400 million customers in 24 countries, operates at 50 Hertz. That means that, across the continent, energy-generating turbines spin 50 times per second. In 2022, shortly after the beginning of the war in Ukraine, both Ukraine and Moldova synchronised their grids with Europe's. The move had been planned years in advance, but the actual switch was carried out within weeks. For historic reasons, the grids of the Baltic states are still synchronised to the Russian and Belarussian grids, but they, too, are set to sync with the continental European grid in early 2025.

FIGURE 2.9 Existing electricity interconnectors (as of 1 February 2024)

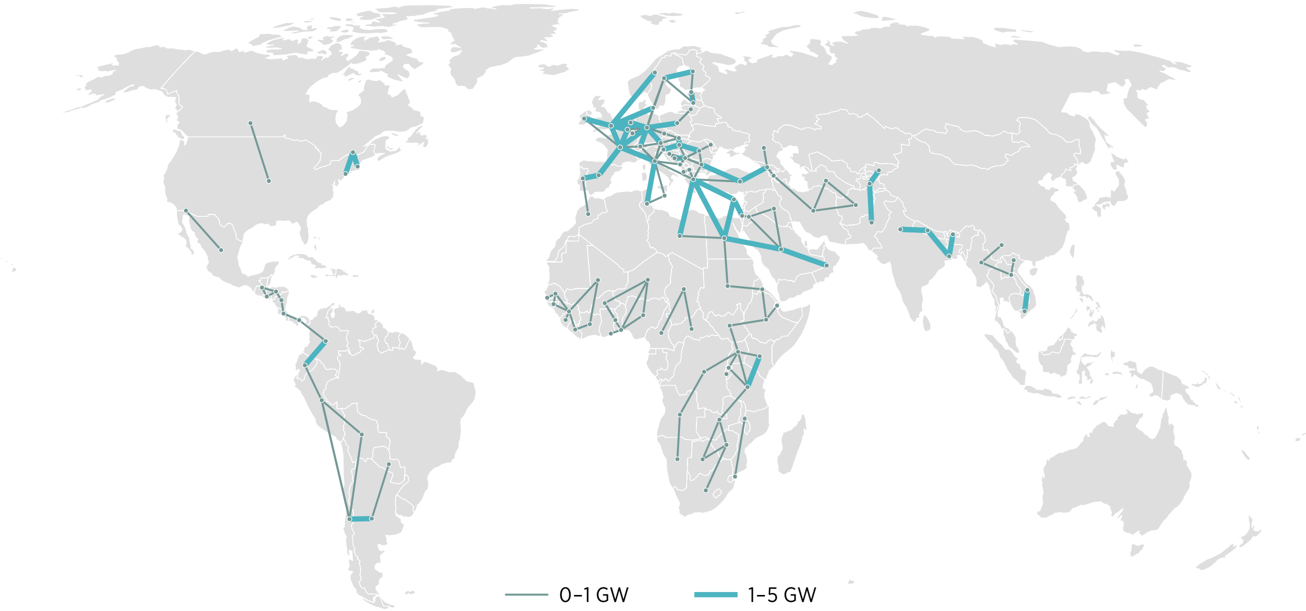


Source: (Brinkerink *et al.*, 2024)

Note: Maps include only cross-border interconnections.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

FIGURE 2.10 Planned electricity interconnectors (as of 1 February 2024)



Source: (Brinkerink *et al.*, 2024)

Note: Maps include only cross-border interconnections.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Connecting national grids allows shared benefits, but it also creates the risk of shared problems, such as cross-border cascading outages. An issue in one part of the grid, such as a plant failure, could cause a change in frequency to ripple throughout the entire network. Such events have happened before, with large-scale blackouts affecting millions of people in 2003 in North America, in 2006 in Europe and in 2012 in India. In these instances, the risk cascaded mainly within national grids; however, with the expansion of cross-border interconnectors, these risks could extend beyond national borders.

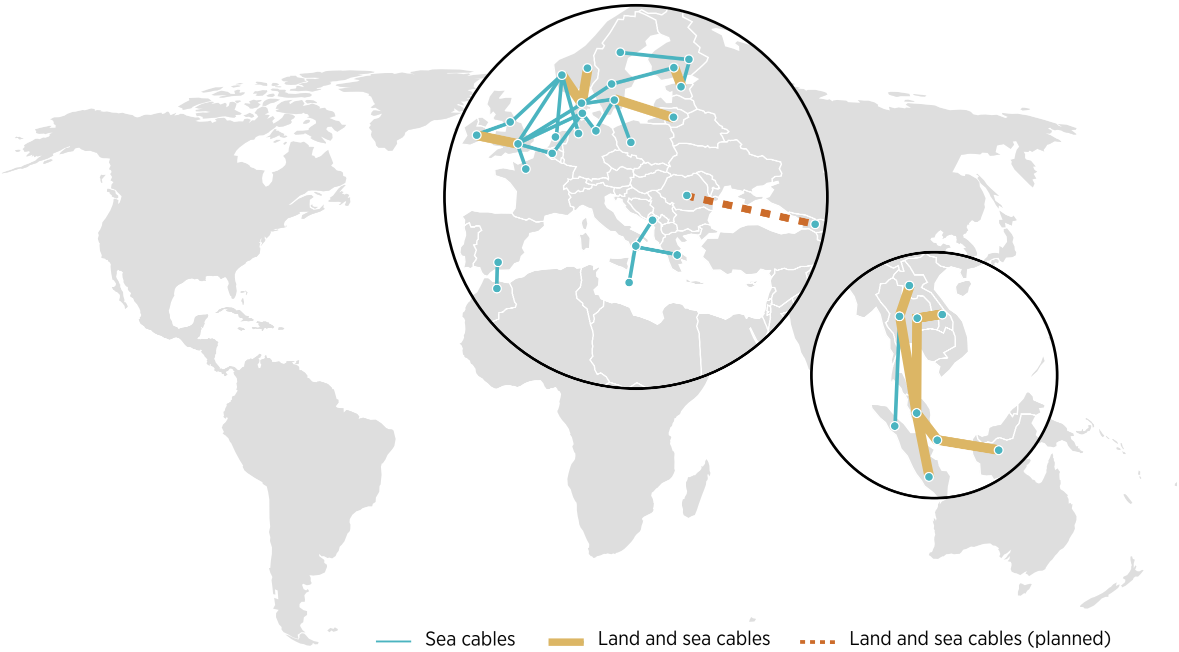
In principle, interconnected grids also create risks of deliberate disruptions. During the 2022 energy crisis in Europe, for instance, there were fears that some countries would curb electricity exports to their neighbours (Le Monde, 2022). However, actual instances of cuts in electricity exports are rare. A recent example is Russia cutting exports to Finland in May 2022 over disputes related to sanctions that affected payments, which led Finland to lose 10% of its electricity supply (Reuters, 2022). The impacts of the rare instances when electricity is used as a weapon are muted so long as importing countries maintain proper capacity margins and significant capability to reduce demand during emergencies.

The fact remains that the effects of a cross-border electricity disruption are different from those of an oil or gas disruption. First, because electricity imports are grid-bound, their loss can be made up only to the extent the existing grid allows. (Conversely, the exporter's capacity to reroute electricity exports to another country depends on infrastructure availability.) Second, as of now, electricity is difficult to store in significant volumes and for long time periods. Therefore, non-delivered amounts of electricity would probably require the curtailment of energy-generating capacities. Third, since electricity has to be sold and consumed the instant it is produced, the effects of an export boycott would be immediate and could have significant economic and social effects (Lilliestam and Ellenbeck, 2011).

The increase in electrification and the expansion of cross-border energy trade call for a strategic reassessment of what is considered a strategic sovereign asset in a decarbonised and regionalised energy landscape. In this context, interconnectors and electrical grids emerge as critical nodes for ensuring energy security. This shift calls for a profound re-evaluation by policy makers of ownership, security profiles, access to and control of these crucial infrastructure assets.

Ultimately, as countries navigate this transition, the strategic importance of electrical infrastructure in a decarbonised energy economy will become a central theme in energy policy and international relations, potentially leading to new alliances and shifts in geopolitical dynamics. Transmission cables unlock export potential for countries that today export no power, including Cyprus, Indonesia, Nigeria and Sudan. One recent modelling exercise shows that China could conceivably become the world's largest electricity exporter by 2040, with its 2040 exports representing almost 20% of today's global electricity demand (TransitionZero, 2023).

FIGURE 2.11 Subsea interconnections (as of 1 February 2024)



Source: Compiled by IRENA from public sources.

Note: Maps include only cross-border interconnections; this figure is intended for illustrative purposes and might not be exhaustive.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.


© shaunl; iStock

2.5 THE GEOPOLITICS OF TRADE IN HYDROGEN AND DERIVATIVES

In the coming years, hydrogen will be more prominently linked to energy security in several ways. The production of hydrogen from indigenous sources offers a chance to ease the demand for imported fossil fuels, in particular for industry and hard-to-abate sectors. Beyond reducing import dependence, hydrogen could also improve energy security by diversifying the fuel mix, providing flexibility to the grid, enabling energy storage and sector coupling, and increasing the resilience of islands and remote communities (IRENA, 2022a).

Unlike oil and gas reserves, the extraction of which is concentrated in certain locations, hydrogen is a manufactured commodity that can be produced in many places. There are also known deposits of natural hydrogen in the earth's crust. One such deposit was discovered in the late 1980s in Mali and has since powered the nearby village of Bourakebougou. In this case, hydrogen is an extracted commodity. However, a great deal of uncertainty surrounds both the availability of natural hydrogen and the business case for developing wells and bringing it to markets, which requires costly handling and transport infrastructure.

Since renewable hydrogen can be made in many locations where sufficient renewables and water exist (IRENA, 2022a), hydrogen production has the potential to be much more widely dispersed than oil and gas production, making it less sensitive to market and geopolitical manipulation. Some countries have the potential to achieve (near) self-sufficiency in green hydrogen production, including the United States and China. This is not the case in continental Europe or Northeast Asia, and both regions are gearing up to become hydrogen importers. The European Commission has proposed a target of 10 million tonnes of hydrogen production and 10 million tonnes of hydrogen imports by 2030 (European Commission, 2022).

FIGURE 2.12 Hydrogen pipelines, storage and ports (existing and planned, as of October 2023)

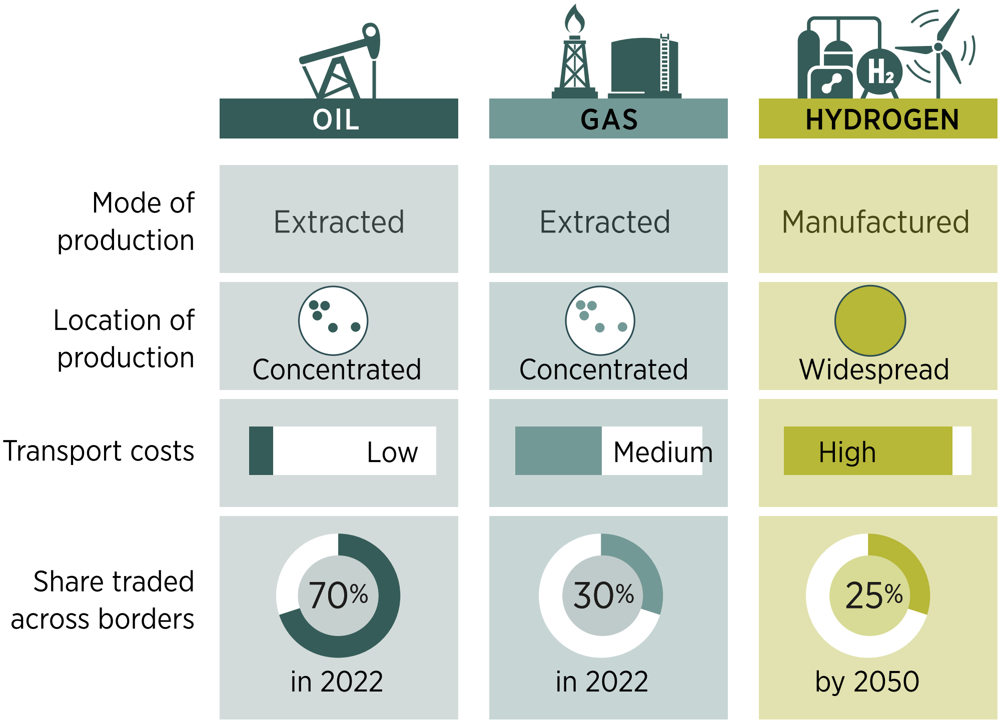
Source: (IEA, 2023b).

Note: The figure displays hydrogen pipelines spanning distances greater than 100 km.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Another major difference between hydrogen and oil and gas is that the costs of transporting the former are much greater, pointing to a less globalised market. Today, most hydrogen is produced and consumed on the same site. Inversely, the high costs and waste associated with hydrogen transportation could spur the development of new manufacturing value chains close to low-cost hydrogen generation centres. This holds important economic potential for many developing countries, if the right policies are designed and deployed and access to finance and technology assured. There remains significant uncertainty regarding the extent to which hydrogen will be traded in large quantities across borders or if industrial activities will shift to renewable-rich areas (IRENA, 2022a; IRENA, 2024).

FIGURE 2.13 The geopolitics of hydrogen and fossil fuels are fundamentally different

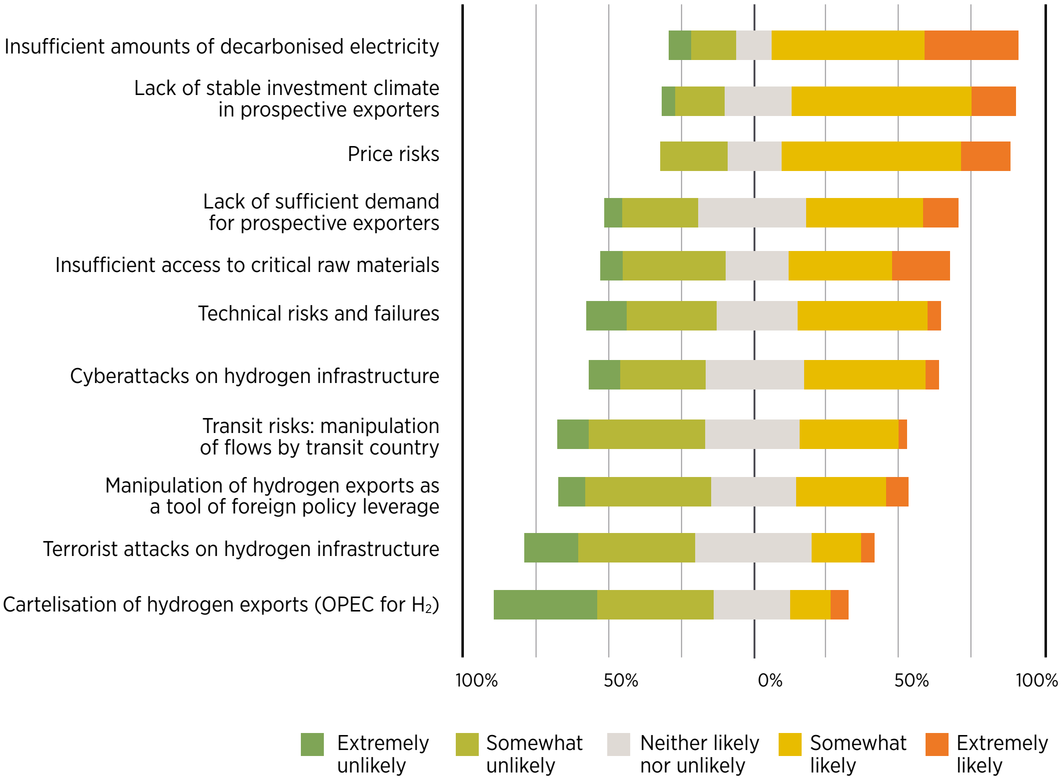


	OIL	GAS	HYDROGEN
Mode of production	Extracted	Extracted	Manufactured
Location of production	Concentrated	Concentrated	Widespread
Transport costs	Low	Medium	High
Share traded across borders	70% in 2022	30% in 2022	25% by 2050

Note: The oil and gas shares are calculated from the EI's *Statistical Review of World Energy (Energy Institute, 2023).* The share for hydrogen is an IRENA estimate.

Introducing hydrogen as an energy carrier can also create energy security risks, especially in the case of traded hydrogen and derivatives. In a survey carried out for IRENA's 2022 study on the geopolitics of hydrogen (IRENA, 2022a), experts assumed that the four most acute risks related to traded hydrogen between now and 2050 are: 1) price risks; 2) lack of a stable investment climate in prospective exporters; 3) insufficient amounts of decarbonised electricity (to produce electrolytic hydrogen); and 4) lack of sufficient demand for prospective exporters (Figure 2.14).

FIGURE 2.14 Expert views on hydrogen energy security risks



Source: (IRENA, 2022b).

2.6 THE GEOPOLITICS OF TRADE IN CRITICAL MATERIALS

The current notion of energy security, which is rooted primarily in concerns over fossil fuel supply, centres on the continuous accessibility of energy sources. A common concern is that dependency on critical materials such as lithium, nickel or rare earth elements will replace fossil fuel dependency.

There is no agreed definition of criticality. Indeed, the selection of which materials should be considered critical is dynamic and driven by national and, at times, regional priorities and considerations. Critical materials came into focus with the growing demand stemming from energy transitions, highlighting the geographical concentration of mining and processing, opaque trade practices, and possible competition with other sectors in which the same materials are used, such as defence, health, information technologies, and space, among others.

While today's market in minerals is indeed highly concentrated, the significant differences between fossil fuels and critical materials must be considered (Figure 2.15). Both must be mined, but materials can be recycled, which means that they have to be mined only once. As renewable energy assets age, and secondary streams of materials become available from recycling, sourcing will also diversify. The overwhelming majority of fossil fuels is combusted and cannot be recycled.

A disruption in the supply of oil and gas can create price hikes and energy shortages, with immediate and widespread effects. By contrast, a disruption in the supply of minerals may make it harder for manufacturers to produce electric vehicles or renewable equipment, but it will not affect those already produced or deployed. Renewable energy technologies already built using those minerals could continue to operate for decades even if supplies of critical inputs are disrupted. Therefore, the risk associated with disruptions in the supply of materials is less about energy security and more about the potential slowdowns in energy transitions.


© ugurhan; iStock

FIGURE 2.15 Critical materials are fundamentally different from fossil fuels

FOSSIL FUELS	CRITICAL MATERIALS
Large mining quantities In 2021, 15 billion tonnes of fossil fuels were extracted.[a]	**Low mining quantities** Some 10 million tonnes energy transition minerals were produced in 2022 for low-carbon technologies.[b]
Generate huge rents Oil and gas exports alone represented a value of USD 2 trillion in 2021.[c]	**Generate smaller profits** Exports of copper, nickel, lithium, cobalt and rare earths generated 96 billion in 2021.[d]
Combusted as fuel Fossil fuels are primarily burned as fuel, accounting for approximately 94% of their usage.[e]	**Input to manufacturing** Critical materials are housed within energy assets that typically have a 10–30 year lifespan.
Energy security risk A disruption in the supply of fossil fuels can lead to immediate energy shortages and price spikes.	**Energy transition risk** Disruptions in the supply of critical minerals can delay the construction of new clean energy assets, but do not affect current energy prices or supply.
Not recyclable Fossil fuels are primarily consumed through combustion and cannot be recovered or repurposed.	**Reusable and recyclable** High potential for reducing use, reusing and recycling.

Source: (IRENA, 2023a).

Notes: [a] Figure is for 2021 and taken from BP's *Statistical Review of World Energy*. Oil and coal figures were available in tonnes; gas data were converted from billion cubic metres (bcm) to billion tonnes using the formula (1 m^3 = 0.712 kg), based on BP's methodology, which is also used by Hannah Ritchie: https://hannahritchie.substack.com/p/mining-low-carbon-vsfossil [b] Based on IRENA calculations, production of materials (copper, lithium graphite, nickel, cobalt, manganese, rare earth elements and platinum group metals) for renewable energy-related technologies in 2022 amounted to some 10 million tonnes (megatonnes). [c] in 2021, exports of crude petroleum (HS 2709) generated USD 951 billion; refined petroleum (HS 2710) generated USD 746 billion; liquefied natural gas (HS 27111100) generated USD 162 billion; and natural gas in gaseous state (HS 271121) generated USD 173 billion. [d] In 2021, exports of copper ores and concentrates (HS 2603) generated USD 91.1 billion; nickel ores and concentrates (HS 2604) generated USD 4.24 billion; cobalt ores and concentrates (HS 2605) generated USD 118 million. With respect to rare-earth metals, scandium and yttrium (HS 280530) generated USD 586 million. [e] Calculated from IEA's *World Energy Balance* (2020), available from: www.iea.org/Sankey.

While important, materials markets are generally smaller than fossil fuel markets and do not generate anywhere near the same revenues as oil and gas do today. Nevertheless, environmentally based trade restrictions on certain critical materials could potentially alter trade dynamics and curtail or redirect flows. Other potential concerns are opacity of supply chains, concentration of production and refining (IRENA, 2023b) and growing trade restrictions for key materials (IRENA, 2023a).

Policy makers must fully understand the links between energy security and the supply chains for materials and related technologies. These are dynamic and can be managed with proactive policy action. Support for R&D to improve efficiency, find alternatives, shape product design and encourage innovation (Box 2.3) can reduce long term vulnerabilities and risks. Diversifying and shortening of supply chains is a priority, as well as making them more transparent, sustainable and responsible.

BOX 2.3 Disruptive innovation

Historically, mineral disruptions and vulnerabilities have often triggered so-called disruptive innovation to add ways to "engineer the way out" of scarcities or geopolitical dependencies. Already, many options for substitution exist. Lithium-iron-phosphate batteries do not use nickel or cobalt; sodium-ion batteries do not require lithium; and copper can be replaced by aluminium in many cases. A recent study also found that levels of supply chain vulnerability vary depending on the material and chemical mix. The chemistry of lithium-iron-phosphate batteries, for example, may currently be vulnerable to supply disruptions in China, but nickel-manganese-cobalt chemistries depend on more materials, opening pathways for supply disruptions in other countries, such as the Democratic Republic of Congo or South Africa (Cheng *et al.*, 2024). Overall, innovations in technology can influence demand by introducing substitutes, enhancing efficiency, optimising design, and incorporating new materials (IRENA, 2023a).

© Joaquin Corbalan P; shutterstock

Recent supply chain disruptions have driven many countries and regions to attempt to localise supply chains for greater strategic autonomy and to reduce dependence on potential adversaries. More specifically, governments are formulating policies to encourage strategic industries to either relocate or establish new operations in their home countries (reshoring), in nearby regions (nearshoring) or in trusted ally nations (friendshoring). Critical and strategic mineral supply chains are also covered by these efforts (IRENA, 2023a).

2.7 THE GEOPOLITICS OF TRADE IN CLEAN ENERGY TECHNOLOGIES

Dependency on technologies and semi-finished products will play a greater role in an electrified, digitalised and decentralised energy system. Technology dependency, however, will be vastly different from dependency on fossil fuels, as previously noted. For example, the disruption in Russian gas deliveries to Europe that began in 2021 created immediate problems because of the need to heat homes and run power plants. An interruption in the supply of a manufactured good would cause no immediate problem for energy security.

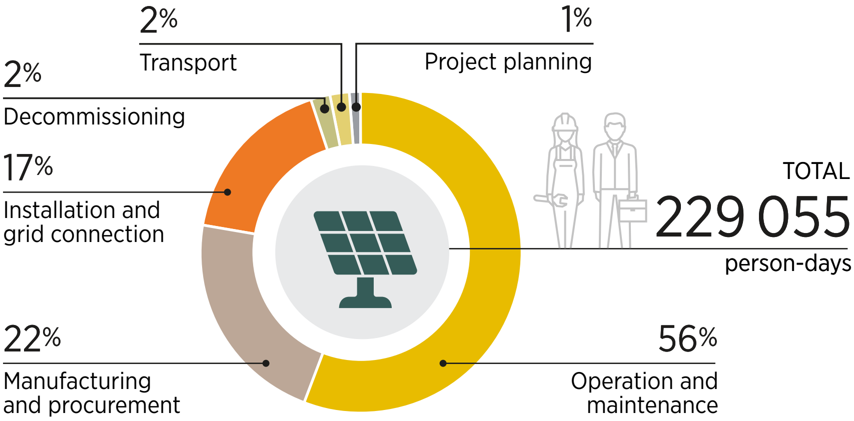
Just as with critical materials, concentration of production in a few key countries can lead to vulnerabilities in the supply chain. Disruptions caused by natural disasters, political instability or trade disputes in those countries can result in shortages or price fluctuations, affecting global energy markets. Countries heavily reliant on imported clean energy technologies may face risks related to technological dependence. For many developing countries, these technologies are out of reach owing to cost (both to buy them and to develop substitutes), intellectual property rights, and worries on the part of technology owners about the potential for technology transfer to geopolitical rivals.

Conversely, efforts to decouple, de-risk or friendshore supply chains for clean energy technologies run the risk of fracturing global clean technology industries along geopolitical fault lines and could hinder the global energy transition by pricing certain technologies too high and shutting out developing countries.

No country masters every aspect of clean technology. Countries are enmeshed in a web, not a chain of dependencies. China, for instance, is the dominant producer of solar PV panels, batteries and electric vehicles, but it depends on other countries for raw materials. China is also the largest installer of many renewable technologies. The bottom line is that manufacturing is not easily separable from installation and consumption (For example, more workers install solar panels than build them [Figure 2.6]. And in most cases, tariffs and other trade protection measures threaten more jobs than they protect).

© andresr; iStock

FIGURE 2.16 Distribution of human resources required along the value chain for the development of a 50 MW solar PV plant, by activity



Source: (IRENA, 2017).

Finally, demographics and the distribution of skills play crucial roles in driving the green industrialisation of developing nations, which in turn can lead to more balanced trade relationships. This factor, often overlooked, is vital in the evolving geopolitics of energy security within renewables-dominated energy systems and is central to the geopolitics of trade in clean technology.

Developing nations, often rich in human resources, have the potential to become significant players in the renewable energy sector. By investing in education and skill development focused on green technologies, these countries can build a workforce adept in the needed fields. Such an approach not only fosters domestic growth but also positions these nations as competitive players in the global clean technology market. Moreover, their integration into the global green economy can lead to a more equitable distribution of economic benefits and technological advancements. It can also help in reducing the global dependency on a limited number of countries, thereby making global energy markets more resilient.

Leveraging demographics and skills development is not just a matter of domestic policy but a strategic imperative that can reshape the global landscape of renewable energy and clean technology trade. It is an opportunity for developing nations to contribute to the resilience of the global energy system while enhancing their own economic and energy security.

© The Desert Photo; shutterstock

© onuma Inthapong; iStock

CHAPTER 3

A MULTI-DIMENSIONAL APPROACH TO ENERGY SECURITY

HIGHLIGHTS

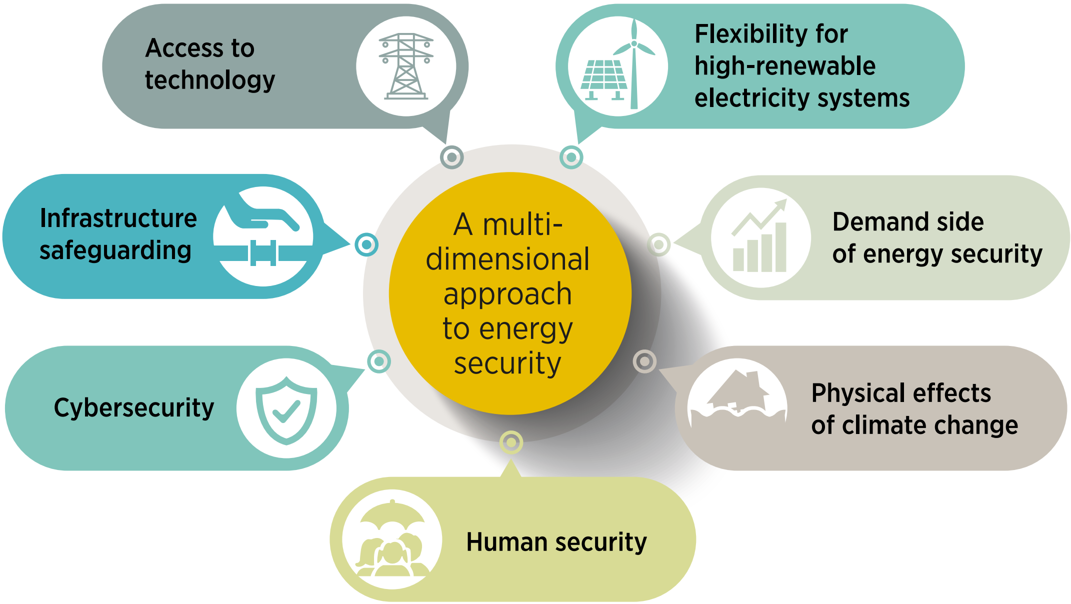
- The supply chains for various technologies in renewables-based systems are embedded in a complex web of connections, and exposed to geopolitical and other disruptions and uncertainties. Given access to technology and resources, developing countries can diversify renewable supply chains, making them more resilient. Such access is also key to an equitable energy transition.
- As the share of renewable energy in the global energy mix grows, flexibility becomes an essential piece of systems' planning, management and governance. Enhancing flexibility, including cross-border power exchange, is thus a key consideration for energy security.
- While the dynamics of supply and demand have always affected energy systems, energy security was addressed largely through supply-side measures. Managing energy demand, historically not considered in the context of energy security, gains paramount importance as a resilience building measure. In increasingly complex and interconnected energy systems, activating the demand side will become key in enhancing efficiency, responsiveness and resilience, as well as ensuring adaptability to both gradual shifts and sudden changes.
- The impacts of climate change on energy supply chains and power systems present growing risks to energy security. Increases in the frequency and magnitude of extreme weather hazards may disrupt commodities supply chains, compromise power system reliability, and damage infrastructure and other energy assets. Any of these can trigger cascading effects across sectors and national borders.
- The interplay of electrification, digitalisation and decentralisation increases the magnitude of, and energy systems' exposure to, a broad spectrum of physical, cyber and hybrid threats. Conventional hard security risks to energy assets may be compounded by cyber attacks, disinformation campaigns and hostile infiltration of energy systems. Understanding these evolving threats, and how they converge and mutually reinforce one another, is necessary to ensure the resilience and security of contemporary energy systems.
- Energy security is critical for human security and development. Threats to human security – such as population displacement, poverty, instability, resource competition, and limited energy access – interact dynamically, amplifying one another and impacting energy security. An integrated strategy is essential to tackle these challenges.

In this chapter, we identify the key elements that must be considered when rethinking energy security for the new energy world. The exponential growth in renewable and other energy transition technologies require forward-looking strategies that navigate current challenges and can be adapted to shifts in the energy landscape. Energy assets and infrastructure are long-lived, so investments today should meet security requirements in the current transitional phase and in tomorrow's systems dominated by renewable energy.

The energy security framework proposed here considers the interplay of technological advancement, global trade dynamics, environmental sustainability, and the imperatives of equity and human security. It promotes a multi-dimensional approach to guide policies and practices reflective of the new realities and empowers foresighted decision-making. While fuel supply will not be as important in renewables-dominated systems, supply chain resilience will gain added value. New dependencies and interdependencies should be examined with a long-term view, given their political and socio-economic relevance.

The systemic shift underway requires holistic thinking across technologies, markets, policies, and institutional and human resources. With a multi-dimensional approach to energy security, countries are better equipped to weigh the benefits and risks of renewables-based systems. Moreover, they are better able to understand and harness the opportunities for co-operation, joint planning, and collaborative management that are the hallmark of these systems.

FIGURE 3.1 A multi-dimensional approach to energy security

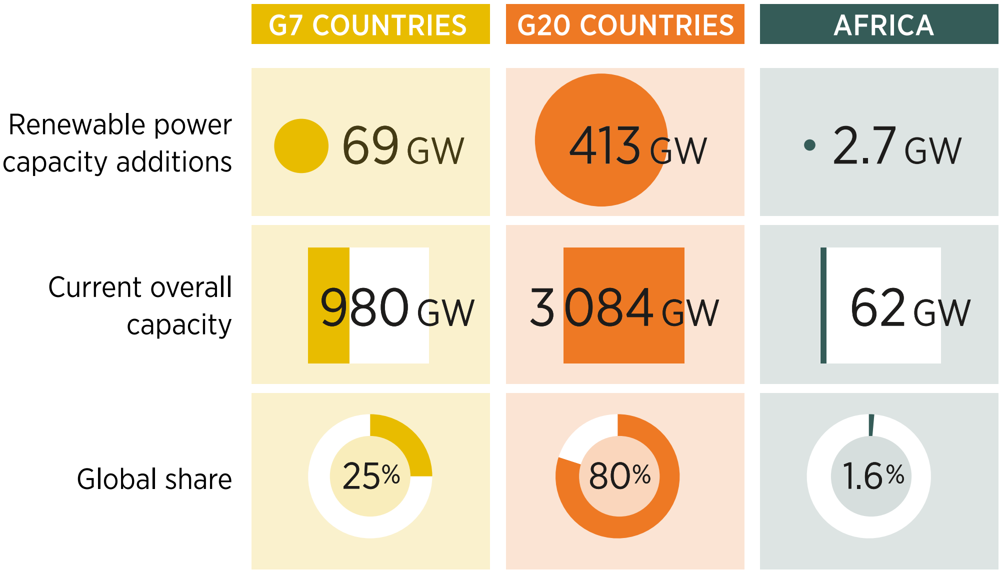


3.1 ACCESS TO TECHNOLOGY

Technologies – not fuels – will play the most critical role in renewables-dominated systems. The supply chains for many of those technologies will be vulnerable to disruptions and uncertainties. Given the urgent need to decarbonise the global economy and the critical role of energy for industrialisation and development in the global south, measures to protect supply chains and expand access to technology must be central parts of energy security frameworks. As a result, fostering supply chain resilience will be imperative for both developed and developing countries to ensure guaranteed access to essential technology.

Regional disparities in renewable energy deployment illustrate a dual trajectory in ongoing energy transitions. Many developing countries lack access to the necessary technologies and financing to provide energy services to their populations. For example, despite its vast potential, Africa accounts for only 1.6% of the global share of renewable capacity (Figure 3.2). This issue extends beyond the energy mix; it reflects the inability to leverage the expansive job market and new economic opportunities that renewable energy presents, opportunities that are readily available to countries with access to technology and finance.

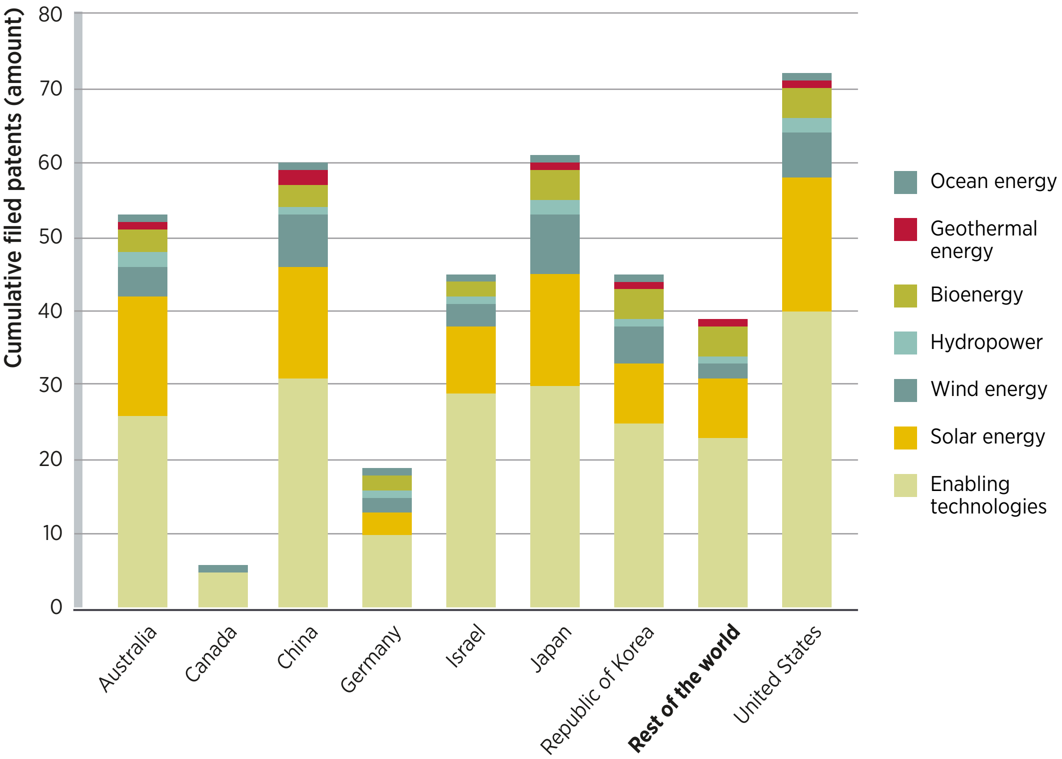
FIGURE 3.2 Disparities in growth of renewable capacity, by selected country groups, 2023



Source: (IRENA, 2024e).

Concentration is observed along value chains. A substantial portion of renewable energy patents are registered in China, the United States, Japan, Australia and the Republic of Korea (IRENA, 2023a) (Figure 3.3). This trend is mirrored in current renewable energy manufacturing, with China dominating 70% of the photovoltaic cell production market (Babayomi *et al.*, 2022).

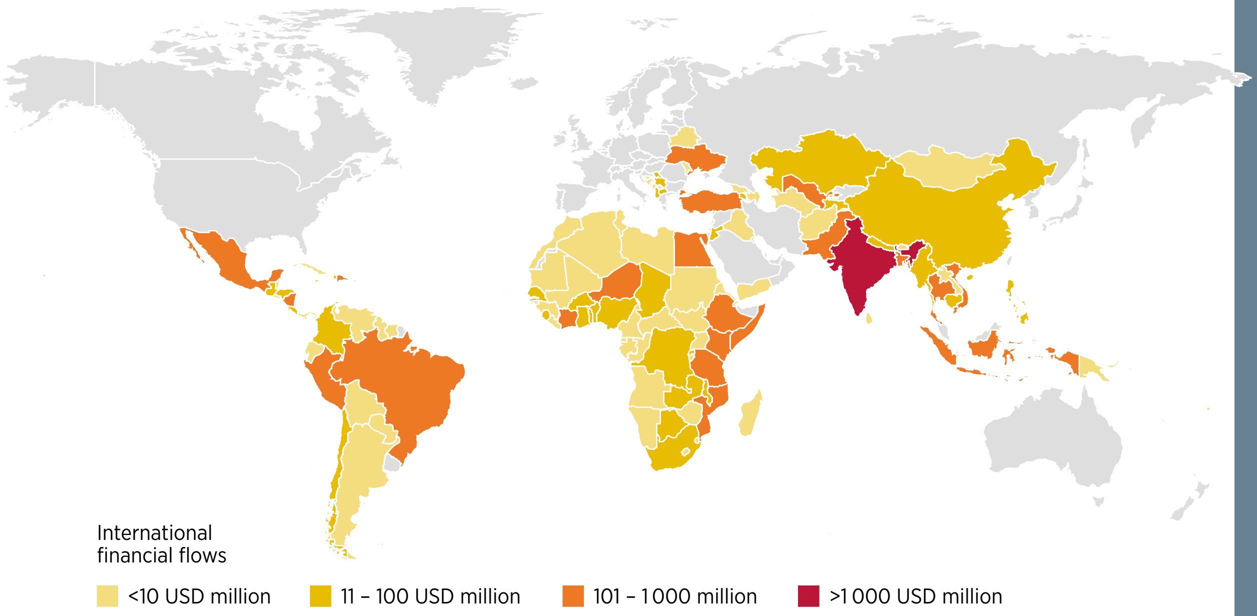
FIGURE 3.3 Top countries filing patents, by technology, 2023



Source: (IRENA, 2024f).

Consequently, many developing countries predominantly serve as consumers of clean technology rather than as innovators or manufacturers (Babayomi *et al.*, 2022). Indicator 7.a.1 of Sustainable Development Goal 7[3] underscores the importance of international financial flows to developing countries in support of research, development and production of renewable energies. Despite this importance, there is a substantial deficit of support, with the flow of finance decreasing in recent years (IRENA *et al.*, 2023). In addition to being a matter of equity and fairness in the energy transition, this deficit influences geopolitical dynamics and poses potential risks to stability.

FIGURE 3.4 International financial flows to developing countries in support of clean and renewable energy (USD million, 2020 PPP), 2021



Source: (IRENA *et al.*, 2023).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

---

[3] *Indicator 7.a.1 of SDG7 is "international financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems".*

Meeting this challenge depends in part on greater diffusion of technology stemming from cost decreases in the global north (IRENA, 2021a). But it also depends on accelerating the present slow pace of transfer of know-how to less developed countries in the South. Consequently, special attention should be paid to the trends of reshoring, onshoring and friendshoring in renewable energy technologies (see section 2.6). These trends can bring benefits to participating countries. Pooling resources, exchanging technologies and know-how, diversifying supply chains, and accelerating innovation can foster green industrialisation and produce significant socio-economic and developmental benefits.

However, such approaches may also fragment clean technology value chains and exacerbate the divide between those with and without access to technology. As countries focus on domestic production and their own supply chains, broader international transfers of technology may be stifled. The shift may particularly disadvantage developing countries that lack the resources and expertise to develop technologies locally. Furthermore, the division of global trade networks into competing blocs could sideline countries not aligned with any of these blocs, depriving them of crucial markets, technologies and investment opportunities.

Such risks underscore the need for balanced approaches to ensure equitable access to energy transition technologies and promote inclusive global development. International transfer of technology and technical know-how will promote socio-economic development in these regions (WIPO, 2015) while also opening new markets that enhance geopolitical stability. A new approach is needed, moving beyond the physical transfer of technologies to recipient countries. The aim should be to build local manufacturing capabilities, create local expertise, and develop favourable conditions for technological growth and acceptance, thus allowing developing countries to fully participate in the creation of resilient energy value chains.

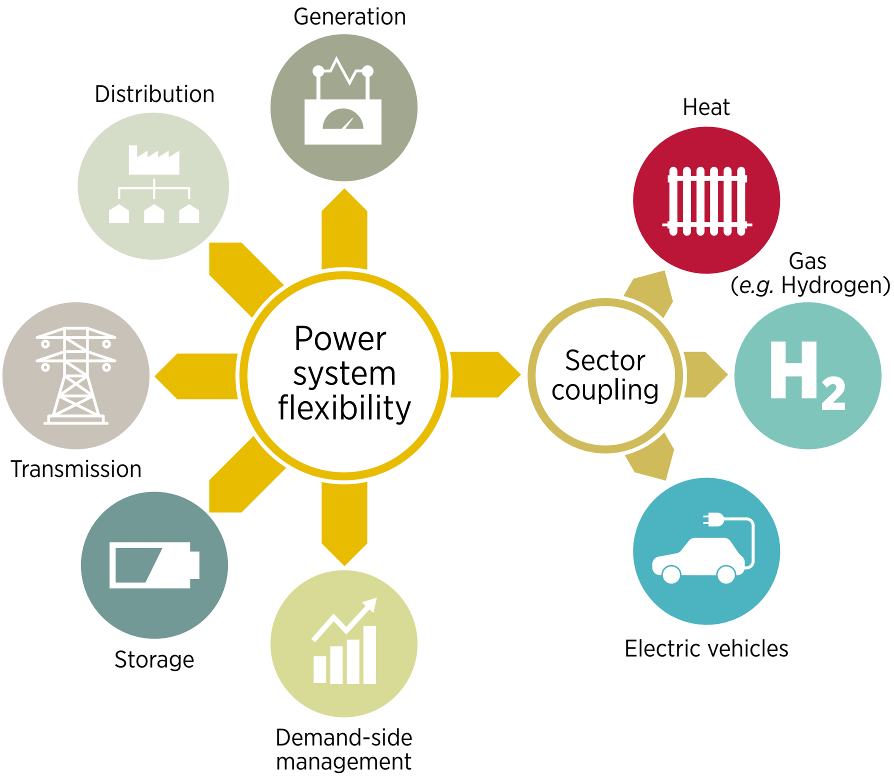
3.2 FLEXIBILITY FOR ELECTRICITY SYSTEMS HIGH IN RENEWABLES

IRENA defines flexibility as the capability of a power system to cope with the variability and uncertainty of solar and wind energy, avoiding curtailment of power from these sources and reliably meeting demand (IRENA, 2018). In simple terms, power system flexibility refers to the ability of power systems to respond to both expected and unexpected changes in demand and supply.

Historically, flexibility was not a major focus in power system planning – or a consideration in thinking about energy security. Instead, baseload was often the watchword. As the share of renewables increases in power systems, the need to think about flexibility grows.

Various aspects of the system contribute to its flexibility, including the deployment of electric vehicles equipped with smart charging and vehicle-to-grid capabilities, production of green hydrogen, battery storage and demand response (IRENA, 2020a) (Figure 3.5). In the longer term, coupling energy demand across sectors – such as heat, fuels, and mobility – via power-to-heat, power-to-gas, and power-to-mobility technologies offers significant flexibility while advancing decarbonisation efforts (IRENA, 2018b). Power plants using hydrogen or ammonia generated from renewable energy power can also play a key role when outputs of variable renewable energy drop. Power exchange across regions is another important way to balance the system. Indeed, interconnections are powerful sources of flexibility (IRENA, 2019).

FIGURE 3.5 Enablers of power system flexibility in the energy sector



Source: (IRENA, 2018a).

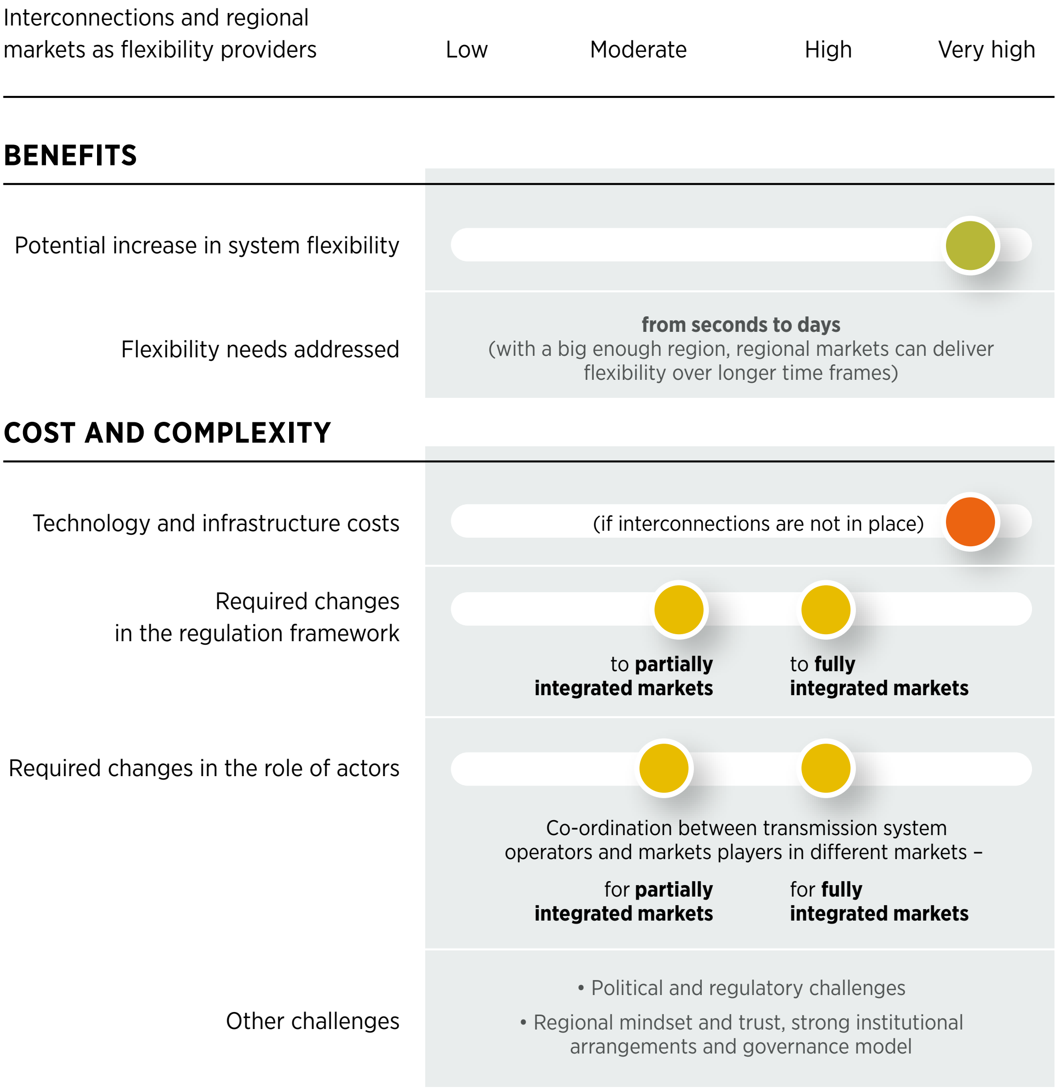
There are risks associated with flexible systems. Energy networks can be targeted by a host of physical, cyber or hybrid threats with the potential to disrupt energy systems. The reliance on shared or interconnected infrastructure necessitates significant investment and maintenance, which is not necessarily assured. Different countries have varying regulatory frameworks, which can complicate cross-border power trade, and harmonisation and compliance can be challenging and costly. Risks associated with supply chains, including the compromise of critical components or software used in the energy sector, can affect cross-border electricity trading. The stability of cross-border power trade can also be affected by political relations between countries. Proactively addressing these risks requires strategic policy making and the identification of alternatives that can be deployed if problems arise.

The development of flexible renewable energy systems relies heavily on access to capital, infrastructure, advanced technology and skilled labour. Without these, countries may struggle to transition to modern systems and fully exploit opportunities. Volumes of investment need to increase, as does their distribution. IRENA finds that 120 developing countries received only 15% of all global renewable investment in the past two decades, with Sub-Saharan Africa receiving less than 1.5%, despite having the highest percentage of energy-deprived people (IRENA, 2024a).

The flexibility inherent in renewables-dominated power systems brings geopolitical and geoeconomic considerations to the forefront. Countries endowed with abundant renewable resources can bolster their geopolitical influence through energy trade, diplomacy and collaboration. The versatility of renewable energy systems results in diverse energy portfolios, thereby strengthening resilience against market fluctuations and disruptions. Strategic investment is thus essential for countries to leverage the advantages of renewable energy flexibility, enhance their competitiveness in sustainable energy markets and effectively manage risks.

© Frame Stock Footage; shutterstock

FIGURE 3.6 Benefits and costs of interconnections and regional markets as flexibility providers



Source: (IRENA, 2019).

© Chong Kee Siong ; iStock

© Sigit123456; shutterstock

3.3 THE DEMAND SIDE OF ENERGY SECURITY

As previously noted, conventional energy security policies have often overlooked demand, focusing instead on supply. This is evident in the International Energy Agency's definition of energy security as the uninterrupted availability of energy sources at an affordable price (IEA, 2023). In recent years, demand for energy has been evolving due to electrification, digitalisation and expansion of energy services, expanding the field of energy security. Rapidly growing global energy demand carries profound geopolitical implications, exerting influence over global energy markets, trade patterns and strategic alliances. In this context, it is reasonable to incorporate the demand side as a key tool in enabling and bolstering energy security.

Electrification is reshaping traditional energy demand patterns to favour both renewables and energy efficiency (Gielen *et al.*, 2019). As more sectors transition towards renewable energy, and with the growing potential of decentralised generation, households, businesses, and communities are becoming active participants in energy production. Clean energy technologies like PV solar panels and batteries allow end users to generate and store their own electricity, thereby reducing reliance on traditional centralised power systems and grid infrastructure.

The process of electrification has increased the number of stakeholders in the energy landscape. Beyond traditional players such as utilities, industries and governments, new actors – such as renewable energy companies, manufacturers of electric vehicles, smart grid operators, and providers of charging infrastructure, energy storage, and distributed energy resources have begun to shape the future of energy. These entities not only expand energy demand, but they also play a role in ensuring energy security. Their engagement with and ownership of the issue of energy security is a key part of the energy transition, reflecting their customers' energy consciousness.

The 2022 energy crisis that engulfed Europe demonstrated the vital role of the demand side of energy security. To cope with the crisis, countries had to quickly put in place measures to control how much energy was being used, including reducing peak power usage, improving efficiency and limiting consumption to ensure the system's resilience. Those measures fostered resilience in the face of a sudden energy shock without compromising service provision or raising costs or emissions. A recent study confirmed that demand-side actions outperform conventional supply-side approaches at making countries more resilient to potential energy security risks (Bento *et al.*, 2024).

As electrification expands, demand-side measures will also be vital to reduce network congestion and optimise transmission and distribution capacity. It will likewise be a powerful lever for system balancing and flexibility, especially in periods traditionally associated with demand peaks, notably surges in demand for heating during cold spells and for cooling during periods of extreme heat.

Managing demand to enhance energy security will not happen automatically. Foresight and planning will be required. Demand-oriented strategies depend for their success on improvements in energy efficiency and the deployment of demand-response measures, such as load shifting, smart grid technology and increased automation, all acting together to reinforce energy security. Mechanisms such as critical peak pricing and monetisation of demand reduction have yielded considerable benefits in jurisdictions across North America and Europe (Bakare *et al.*, 2023a; Faruqui and Sergici, 2010), so the approach is not without precedent, but it will have to be deployed at a larger scale as the transition accelerates.

More broadly, strategies will be needed to address energy demand at its deepest, structural roots. These will involve urban planning and smart growth, energy efficient building design and construction, promotion of sustainable transportation, and educational and awareness programmes. Effective demand-side management promises to enhance flexibility and forestall some of the prohibitive costs of energy system upgrades (including new distribution and transmission development), thereby facilitating efforts to reduce energy poverty. In summary, energy efficiency, demand-side responses, and load optimisation can be powerful and cost-effective ways to improve energy security. They also enhance system flexibility with significant environmental, financial and societal benefits.

© Nisangha; iStock

3.4 HARD SECURITY THREATS TO INFRASTRUCTURE

Traditional threats to energy systems, such as physical attacks on infrastructure or disruptions due to conflict or strategic manipulation, remain critical concerns for energy security. The integrated and interconnected nature of modern energy systems may amplify the significance of such threats. The potential targets are numerous, and range from production facilities, ships and pipelines transporting energy commodities, to storage facilities, power grids and cross-border interconnectors.

With electricity networks forming the backbone of modern societies, the impact of physical attacks on energy systems can be far-reaching. Severe damage to the electric grid can have a cascading negative effect, crippling essential services such as health care and social services, as well as curtailing economic activity. The repercussions can extend beyond immediate service disruptions, potentially leading to social unrest and escalating instability.

The ongoing electrification of the energy sector brings additional considerations to the fore. This shift is largely driven by digitalisation, automation and decentralisation, resulting in a multitude of interconnected smart components, such as networked electric vehicles, household appliances and metering devices, all integrated with the electrical grid. Such systems are also becoming increasingly interconnected on a cross-regional or even transcontinental scale.

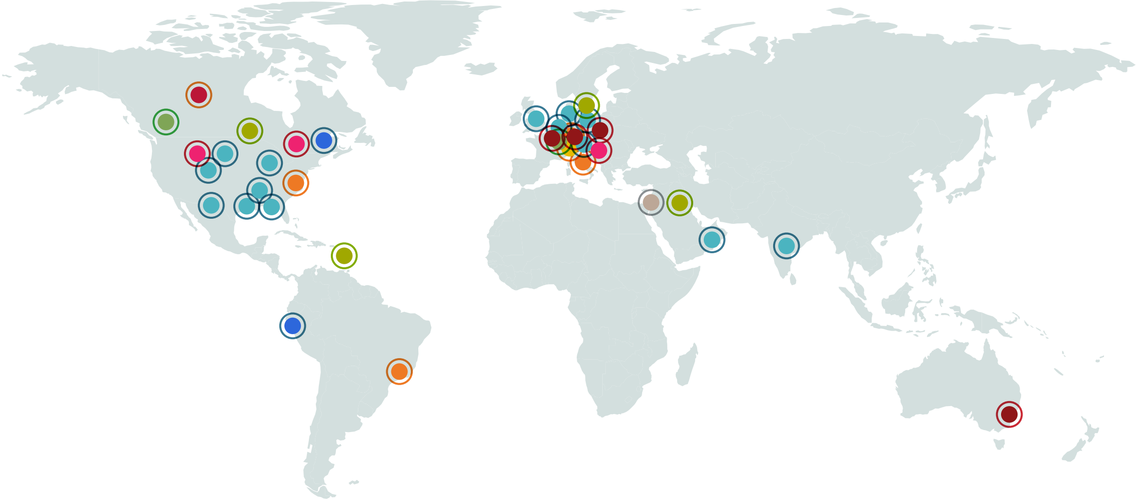
The advancing digitalisation of society increases the exposure of energy systems to a new spectrum of risks. The rising prevalence of hybrid threats that combine physical and cyber elements could compromise the functionality and operational effectiveness of entire energy systems, with far-reaching implications for energy security, human security and state security (EEAS, 2020). The increasingly interconnected nature of networks means that a hybrid threat targeting an energy system in one country could have cascading effects beyond its borders. Tactical investments in energy-related infrastructure as a means of infiltrating energy systems, are also part of the hybrid warfare toolbox. The growth of offshore and seabed energy infrastructures presents still more challenges. These installations often operate in areas where jurisdictional responsibilities for security are less clear, potentially creating more vulnerabilities.

Understanding the evolving nature of these threats and their interplay is crucial for the design of effective strategies and response mechanisms. Addressing them calls for a comprehensive set of tools and measures and necessitates multi-disciplinary collaboration extending beyond traditional energy sector stakeholders. It demands not only technical expertise but also strategic foresight and robust international co-operation involving military experts, public cyber-defence bodies, academic institutions, and civil society (Wiggel *et al.*, 2021).

3.5 CYBERSECURITY

Cyber threats can increase the magnitude of physical attacks or sow disruption on their own. Such attacks include malware, hacking, phishing campaigns, denial of service, or the remote use of electromagnetic pulse weapons to disrupt electricity flows. According to a 2023 analysis on cyber attacks in North America, energy companies account for a fifth of all attacks, making the industry the primary target, with oil and gas companies at most elevated risk (IBM, 2024) (Figure 3.7). Cyber attacks against the EU power grid are also surging (Jack, 2023). Data on other regions is scattered, but it is safe to conclude that cyber risks to energy systems will grow in scale and geographic scope.

FIGURE 3.7 Major cyber attacks on the energy industry, 2023



●	January	Canada	Baker Lake, Energy supply company
●	February	Italy	Energy supply company
		Brazil	Rio de Janeiro, Service provider
		Germany	Karlsruhe, Utility
		US	Houston, TX Oil and gas producer
●	March	Switzerland	Zurich, ZH Technology company
●	April	Canada	Montreal, QC Energy supply company
		Peru	Arequipa, Energy supply company
●	May	Denmark	Energy companies
		India	Jabalpur Energy supply company
		Germany	Munich, Energy tecnology
		Netherlands	The Hague, Petroleum company
		Netherlands	Arnhem, Power grid operator
		Oman	Oman Oil and gas
		UK	Oil and gas
		US	Oak Ridge, TN, Consortium
		US	Energy supply
		US	Houston, TX, Logistics
		US	Oil and gas
●	May	US	Houston, TX, Oil and gas
		US	Carlsbad, NM, Radioactive waste
		US	Austin, TX, Service provider
●	June	Germany	Güglingen, Solar parks
		Canada	Calgary, AB Petroleum company
●	July	Israel	Haifa, Oil Refinery
●	August	Austrialia	Sydney, NSW, Service provider
		France	Paris, Energy supply company
●	October	Germany	Meschede, Energy supply company
●	November	US	Idaho Falls, Nuclear research laboratory
		Slovenia	Ljubljana, Energy supply company
		Germany	Gevelsberg, Energy company
		Canada	Richmond Hill, ON, Pipeline operator
●	December	Curaçao	Willemstad, Utility
		Denmark	Holstebro, Energy supply company
		Iran	Petrol stations
		US	Afton, WY, Energy supply company

Source: (KonBriefing, 2023).

Notes: UK = United Kingdom; US = United States.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Hacking an energy network for commercial purposes (to access sensitive information for commercial advantage) or for financial purposes (ransomware attacks) can also have a severe impact on the energy system (European Commission, 2023a). This was illustrated in 2021, when the Colonial pipeline – one of the longest oil pipelines in North America, providing around 50% of the oil on the East Coast – was brought to a halt by hackers demanding ransom (Bing and Kelly, 2021). Serious ransomware attacks were carried out against Brazilian Copel and Electrobras utilities in the same year (Nakashima *et al.*, 2021).

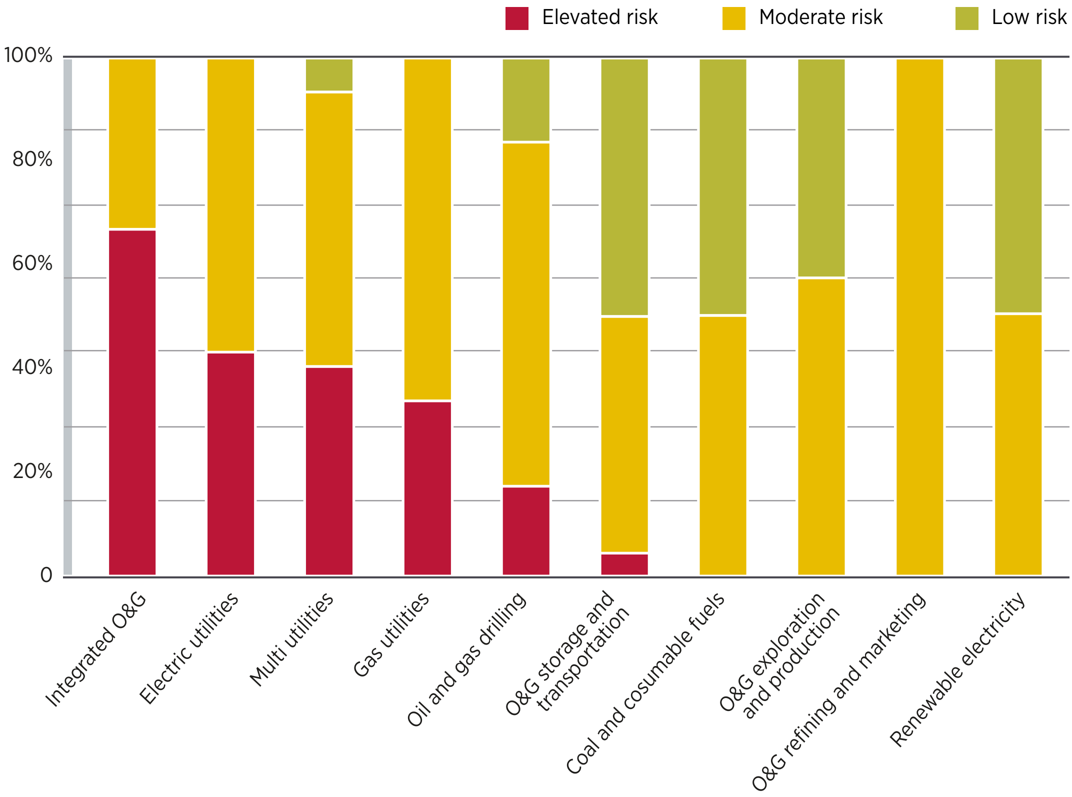
Apart from direct damage or interruption of supply, cyber takeovers of smart sensors or supervisory controls can compromise network reliability, with severe consequences for energy security. Cyber malware may have contributed to the unprecedented blackout that affected 50 million people across the United States and Canada in 2003 (Erbach and O'Shea, 2019). Jamming and spoofing of global navigation satellite systems could be extremely damaging to renewable energy generation (Rügamer *et al.*, 2015). In 2022, cyber attacks disabled the operations of wind farms in Europe (Stupp, 2022). Phishing attacks are also of increasing concern (Jack, 2023).

Less severe as an immediate disruption, but one bearing long-term consequences, could be the use of cyber espionage in the energy sector, as when a sophisticated actor infiltrates and gains access to strategic and sensitive energy system information. The threat to energy systems from such operations has been identified as a key risk by recent NATO analysis, and by the European Union (Dupuy, A.C., *et al.*, 2021; European Commission, 2023b).

As energy systems grow in complexity and digital technologies become essential for operational effectiveness and optimisation, the spectrum of potential threats and the variety of actors capable of compromising energy systems expand correspondingly. The critical nature of energy systems means that any significant threat to them can have far-reaching consequences, extending well beyond the energy sector itself. Therefore, it is imperative to establish advanced, agile and comprehensive strategies for risk management and to stress-test the system against emerging attack entry points. These strategies must be able to ensure the resilience of energy systems in the face of potential threats, thereby safeguarding other critical societal systems. Cybersecurity must become a cornerstone of policy planning and strategies – and a prerequisite for planning of smart grids and cross-border transmission capacity.

© Gorodenkoff, shutterstock

FIGURE 3.8 Energy sector companies at risk of successful cyberattacks (% of companies), by industry, May 2023



Source: (ISS, 2023).

3.6 PHYSICAL EFFECTS OF CLIMATE CHANGE

Extreme weather events induced by climate change are increasingly prevalent, posing significant risks to energy security worldwide. These risks permeate every aspect of energy systems, including energy supply, transport and demand. As temperatures continue to rise, the frequency and severity of extreme weather events and climate shocks will increase.

Climate-related hazards already threaten energy supply in various ways (Figure 3.9). Coastal infrastructure critical for hydrocarbon extraction and processing is particularly vulnerable to tropical cyclones and rising sea levels. Current estimates suggest that about a quarter of refineries are exposed to risks from tropical cyclones, and a third are vulnerable to the effects of sea-level rise. Moreover, thermal power plants become less efficient as ambient temperatures increase, leading to decreased production or shutdowns (IEA, 2022a; United Nations Office for Disaster Risk Reduction, 2022). For example, warmer river waters often exceed legal limits for cooling water discharge from nuclear reactors, leading to reduced energy production at the time when demand for electricity is high.

Transporting energy resources also faces escalating risks from climate hazards. Damage to pipelines, ports and storage facilities can disrupt the flow of energy, amplifying supply chain disruptions. Droughts and low water levels can disrupt vital energy shipping routes like the Panama Canal or the Rhine River. Additionally, extreme weather events can hinder the functioning of electricity transmission and distribution networks. Presently, approximately 20% of global electricity networks face high wildfire risk, 25% are exposed to severe storms, and 10% to tropical cyclones (IEA, 2022b).

Climate change alters energy consumption patterns, increasing demand during periods of extreme weather. Heat waves drive up the need for cooling, while cold snaps heighten heating requirements. Such spikes in demand often coincide with periods when energy infrastructure is more vulnerable, creating a negative feedback loop that exacerbates the challenge. For instance, in July 2021, a series of unprecedented heat waves strained California's power grid due to cooling demand, while a wildfire threatened the transmission lines from the Pacific Northwest. Increased reliance on desalination for freshwater supply can affect demand for energy in water-stressed areas (Yalew *et al.*, 2020).

Climate change is also causing disruptions to renewable energy systems. It is estimated that 14% of hydropower is at risk from tropical cyclones. For instance, Cyclone Idai caused an 80% drop in hydropower generation in Malawi (Bakare *et al.*, 2023). Extreme weather events can compromise the efficiency of wind and solar farms. Offshore wind parks are designed to shut down during heavy storms, while solar PV panels become less efficient under extreme heat.

But although renewable energy sources are weather- and climate- dependent, the impacts of climate change vary and can be mitigated. Wind and solar farms are often spread geographically, which makes them more resilient and reduces the chances of being affected by the same extreme weather event (Perera *et al.*, 2020). Unlike fossil fuels and nuclear power, they do not require significant amounts of water for cooling processes. This makes them less vulnerable to water shortages caused by droughts. The diversification of energy sources, in which each component has different vulnerabilities, also increases resilience.

Energy security strategies must include adaptation to changing climate conditions. Adaptation responses across various sectors could leverage renewable energy to provide cost-efficient, integrated, and reliable solutions for climate adaptation (IRENA, 2021b). Unfortunately, the current focus of policy and related investment is inadequate. Climate adaptation-related investments in the energy sector stood at just over USD 300 million annually in 2019-2020 (WMO, 2022). Insufficient policy attention hinders essential steps such as 1) rethinking the location and design of energy assets and infrastructure to enhance resilience, 2) improving construction methods, 3) formulating contingency plans for extreme weather, and 4) enhancing early warning systems and emergency response strategies to temper the impact of extreme events on energy supply chains.

FIGURE 3.9 Exposure of electricity generation assets, network and supply chains to climate-related risks

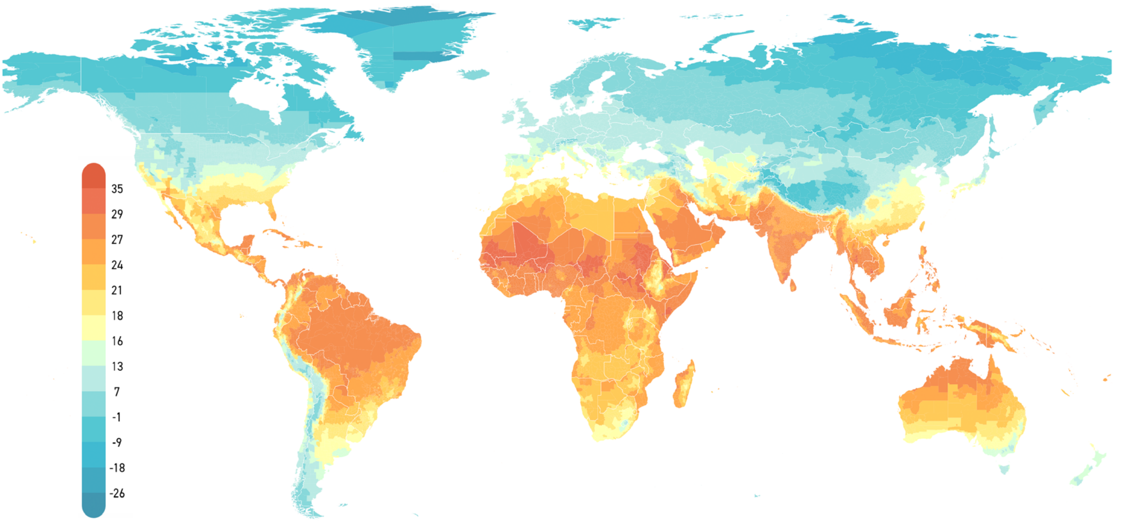
EXTREME HEAT	DROUGHT, ARIDITY AND DESERTIC CONDITIONS	SEVERE STORMS	MEAN PRECIPITATION AND FLOODS	COLD SPELLS, SNOW, ICE AND FROST	WILDFIRES
Affects wind turbine operation	Increased thermal insulation needs for H_2 transport and storage	High winds cause excessive mechanical loading on turbines	Change in water inflows impacts flood control	Ice and frost on wind blades of the turbines affect their operation	Smoke and debris can reduce solar farm output
Risk to H_2 ports and shipping	Reduce cooling water levels and restrict flow rates	Wind turbines shut down to prevent wear and tear	Overtopping of hydropower dams	Risk of undercooling	Interrupt and damage power systems
Impacts generation capacity and operation	Thermal plants shut down because of insufficient cooling	Performance of ACC and cooling towers	Lower cooling system performance of thermal and nuclear plants	Increased pressure on dams and reservoir structures	Difficult physical access to stations
Reduced photovoltaics output	Desert dust reduces solar farms' output	Lightning strikes on wind blades cause cracks compromising their mechanical integrity	Erosion of underground cables	Hail can severely damage solar panels	
Overheated transformers in substations	Risk of insulation failure, increased underground grid faults	Trees falling onto overhead power lines	Risk to distribution system secondary substations, transformers, and underground cables	Risk of forming ice sleeves on bare power line conductors	Trees falling onto overhead power lines
Expansion in pipelines and increased risk of rupture	Risks to shale oil and gas production	Threats to coastal oil and natural gas production sites	Degradation in quality of coal	Increased risk of pipelines freezing and transportation delays	Production shutdowns and resource loss
Threats to fossil fuel transport and storage	Threats to shipping	Risk to coastal refineries and LNG ports			

Hydropower Wind and solar Thermal and nuclear Systems

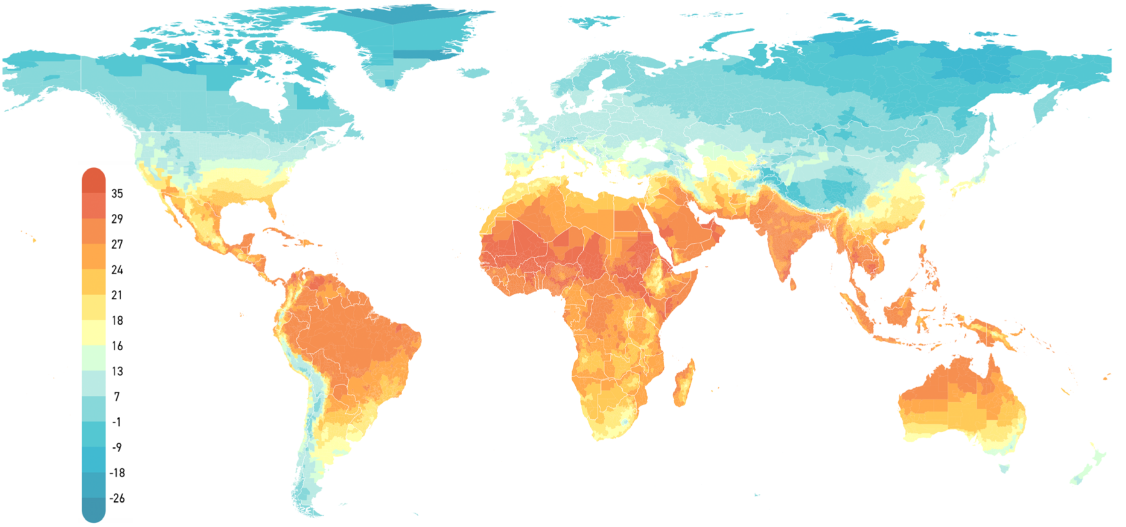
Source: (Eurelectric, 2022; IEA, 2022a).

FIGURE 3.10 Climate impact map

Average annual temperature, medium-high emissions, median probability, 2020–2039



Average annual temperature, medium-high emissions, median probability, 2040–2059



Source: (Climate Impact Lab, 2023).

Notes: Climate Projections on Impact Map are based on the World Climate Research Programme's Sixth Coupled Model Intercomparison Project, known as CMIP6. Damage (cost) Projections are based on the previous round of scenarios, CMIP5.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

3.7 HUMAN SECURITY

The concept of “human security” is often used to describe the root causes of geopolitical instability. Looking beyond military threats to state security, this concept expands the security agenda to include non-traditional threats such as climate change, poverty and disease, which can undermine peace and stability within and between countries. The United Nations General Assembly (2012) has endorsed this principle, which informs the United Nations’ work in areas ranging from peacebuilding to humanitarian assistance and sustainable development (IRENA, 2022a).

The Agenda 2030 and 17 Sustainable Development Goals (SDGs) reflect the multi-dimensional nature of human security (Figure 3.11). Goal 7 calls for ensuring access to “affordable, reliable, sustainable, and modern energy for all”.

FIGURE 3.11 Energy and the Sustainable Development Goals

Source: (IRENA, 2017b).

Some countries have recognised the need for an expanded understanding of energy security, one that extends beyond availability and affordability of energy to establish a stronger connection with human security. India's Integrated Energy Policy of 2006, for instance, defines energy security as "the ability to supply lifeline energy to all citizens irrespective of their ability to pay for it, as well as meeting their effective demand for safe and convenient energy to satisfy their various needs at competitive prices, at all times, and with a prescribed confidence level, considering shocks and disruptions that can be reasonably expected" (Noronha, 2012).

Moreover, most countries have introduced net-zero strategies and have initiated energy transitions focused on air pollution, job creation or other goals. As such, energy security frameworks that focus solely on national security, economic priorities and military needs leave out these important aspects, which intersect with human security.

Meanwhile, the adverse effects of energy on human security are increasingly subject to legal challenges. Climate litigation, for instance, is becoming a strategy to compel countries and companies to address climate change. As of December 2022, there have been 2,180 climate-related cases filed in 65 jurisdictions, including international and regional courts, tribunals, quasi-judicial bodies, or other adjudicatory bodies, such as Special Procedures at the United Nations and arbitration tribunals (UNEP, 2023).

An expanded approach to energy security that includes human security would help address several current omissions. First, it would include underserved populations. Currently, almost 600 million people residing in some 70 countries do not have access to energy, and billions remain underserved. For instance, it is estimated that close to 1 billion people in low- and lower-middle-income countries are served by health-care facilities without reliable electricity access or with no electricity access at all. Only half of hospitals in Sub-Saharan Africa have access to reliable electricity (WHO, *et al.*, 2023). Even if a country achieves a stable and affordable energy supply, energy poverty may exist. This issue has become increasingly apparent in industrialised nations, where energy poverty has risen in the post-COVID era. Many citizens have faced reduced access to essential energy services due to job losses or energy costs, also resulting in public protests and unrests (Carfora *et al.*, 2022).

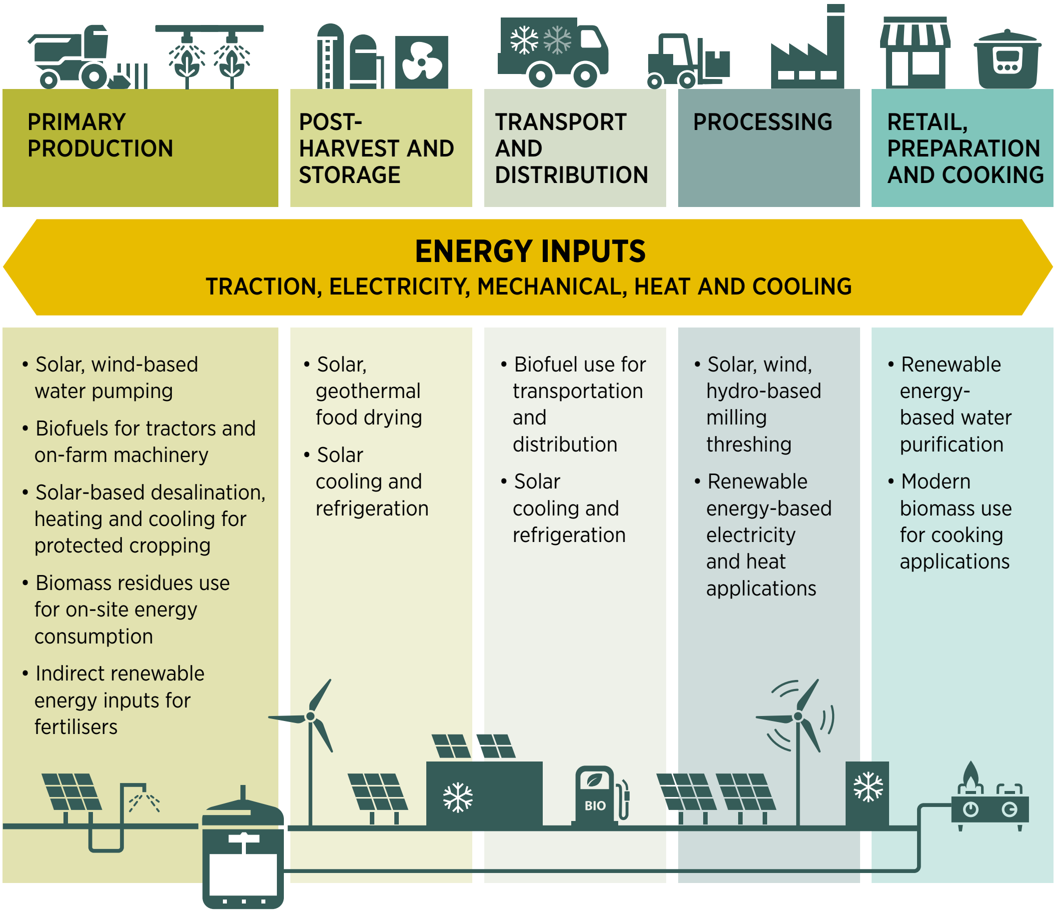
Second, with decentralisation of energy, citizens have moved from the status of bystanders to that of active participants, changing the power dynamics in energy production, distribution and decision-making. Wide participation in the energy system is a powerful tool for demand-side management, given the increased awareness and ownership of the citizenry. Other significant opportunities are arising across sectors, business and communities. For instance, deploying renewable technologies along the agri-food chain would bring increased revenues, greater energy and food security, and reduced greenhouse gas emissions (Figure 3.12).

At the same time, energy security risks come with wider participation. Decentralised systems are more complex to manage, and participation by diverse stakeholders requires robust security systems, as it can increase the risk of cyber-attacks on digital infrastructure (Fearn, 2024).

Third, the social impacts of energy policy, especially in the context of just transition, can have significant consequences, with geopolitical ripple effects. Establishing fair and effective policies and regulations requires considerations beyond energy security or transition strategies. For instance, decentralised systems may deepen energy inequalities if only those with means can participate in the system. At the same time, policies aimed at transitioning away from fossil fuels can have unexpected effects. A recent example is the Gilets Jaunes (Yellow Vests) movement triggered in response to a proposed increase in the tax on diesel fuel in France (Tainturier, 2020). The movement turned into a large-scale social movement, expanding to other European countries and different causes. Similar protests have also occurred in Canada (over the UN migration pact), Israel and Jordan (over corruption and the high cost of living) (The Guardian, 2018).

Climate change, water and food insecurity, migration, infectious disease, and economic marginalisation and inequality collectively undermine peace and increase geopolitical instability. Energy security underpins human security, so strengthening it would almost certainly yield substantial benefits. Renewables-based transitions offer more opportunities than risks to human security. An energy security framework for the 21st century should therefore make human security a central feature.

FIGURE 3.12 Entry points for renewable energy at different stages of the agri-food chain



Source: (IRENA, 2016).

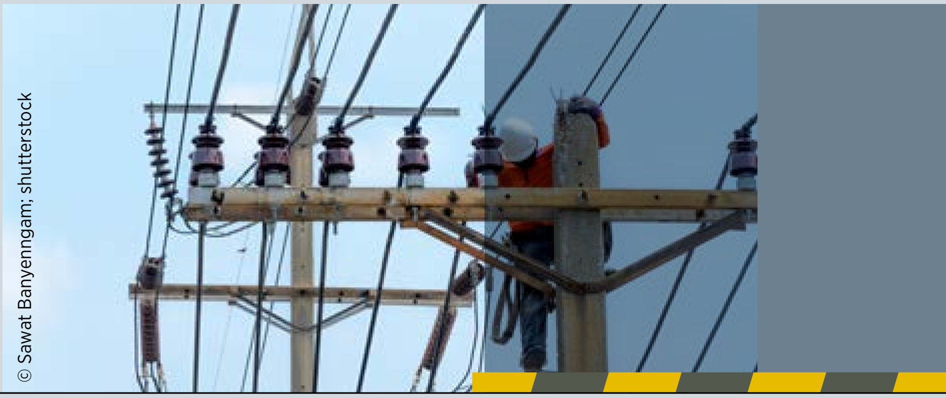
POLICY CONSIDERATIONS

As the share of renewable energy grows in the energy mix, the task of securing energy undergoes a fundamental shift. Where once it was seen primarily as an international concern over access to physical commodities (oil, gas, coal), it has now become an issue of national governance focused on ensuring uninterrupted service. This change will reshape international energy relations, reducing the geopolitical and trade influence of oil and gas, and elevating the role of electrification, cross-border trade and access to technology. Renewables may not offer total energy independence, but they do offer opportunities for countries to enhance their energy security and resilience based on their resources and strengths (Global Commission on the Geopolitics of Energy Transformation, 2019).

Integrating a multidimensional and holistic approach to energy security in policy making promises to help manage the challenges of transition while building a resilient energy system for the future. Advancing the energy transition in line with climate and development goals, underpinned by the principles of just transition, requires speed and prudence in equal measure.

Some key considerations for policy makers are outlined below.

Energy security frameworks must evolve to become effective tools for investment, equitable transition and international co-operation.
Most often, energy security considerations arise at a time of crisis, placing the focus on short-term solutions. But given the systemic and structural nature of the ongoing energy transition, security frameworks should be designed for the long term, integrating wider socio-economic and global aspects. Today's policies and investments prioritising domestic renewable resources, modernisation and expansion of infrastructure, and institutional and human capacity will strengthen energy security in the medium to long term. Energy efficiency and conservation must continue to be central components of comprehensive energy security strategies. Collaboration with other countries is essential to harness opportunities in energy investments, technology and innovation, and governance. The powerful potential of decentralised, resilient systems is only augmented by considerations of human security and people-centred governance, where negative spillovers across sectors and communities are anticipated and mitigated.



© Sawat Banyenngam; shutterstock

Investments in energy assets and infrastructure today should consider energy security requirements both in the transitional phase and in the long term.
Fixed infrastructure is long-lived, so investment decisions should be assessed through a long-term lens. Every investment and planning decision around energy infrastructure and broader industrial value chains today should consider that the geography of a decarbonised economy is likely to be very different from what currently exists. Significant electrification of end uses will reshape demand. On the supply side, renewable power will be traded with neighbouring countries, and hydrogen production will likely occur in locations other than today's oil and gas fields. The increase in decentralised generation will also alter established relationships in generation and transmission. New infrastructure will need to be strategically planned and built to accommodate these shifts. The technical challenges and economic costs of plans to repurpose new and planned fossil fuel infrastructure should be accounted for from the outset.

Governments need to carefully assess what constitutes a strategic asset in the evolving energy system.
Policy makers will have to review the ownership and security profile of energy infrastructure, as well as access to and control of that infrastructure. In the context of renewable energy, strategic assets now encompass wind farms, solar panel arrays, grids and more, as well as the technology that supports these resources. Domestic and cross-border grids, the infrastructure supporting electric vehicles (notably charging stations), and advanced energy storage systems are key enablers of the energy transition. Governments must reassess their approach to the ownership and control of these assets. The reassessment may include exploring public-private partnerships, implementing foreign investment screening practices, or setting up regulatory frameworks that ensure fair competition while safeguarding public interests.

By assessing supply chains for energy transition technologies, policy makers can identify strategically important elements and comparative advantages in value chains, enabling them to form partnerships in a timely manner.
Technologies, and not fuels, play the central role in renewables-based energy systems. The capacity to access needed equipment and the intellectual property that underpins innovation gains paramount importance. Presently, intellectual property, inputs to manufacturing (*e.g.* raw materials) and manufacturing capacity are highly concentrated in a few countries. By implication, most countries depend on imports from a relatively small set of locations. In recent years, much attention has been placed on critical materials and hydrogen. Policy makers should expand this focus to a strategic assessment of supply chains behind key clean energy technologies such as heat pumps, batteries, electrolysers, solar panels and wind turbines, among others. This assessment should be three-pronged: identification of key technologies in the domestic context; consideration of how to leverage local capabilities (*e.g.* manufacturing); and strategy for international co-operation and partnerships.

Diversification of suppliers, routes and carriers will help build resilience and should be shaped to promote co-operation and equity.
An energy system that is more diversified inherently possesses greater resilience against external shocks. As the world moves towards decarbonisation, energy trade will shift from oil and gas to energy carriers such as electricity, hydrogen and bioenergy, as well as to green commodities (*e.g.* steel), materials and clean technologies. A diverse market will create new opportunities for trade and co-operation, reduce supply chain risks, mitigate greenhouse gas emissions and improve energy security for all. The success of this strategy hinges on providing comprehensive support to developing countries, including access to technology, technical assistance and capacity building resources, all underpinned by affordable and innovative finance. Conversely, developing countries will need to develop proactive approaches to exploit domestic value and promote regional co-operation for local market creation. When establishing new trade links, countries should consider import risks and dependencies that may arise in the longer term and anticipate impacts of evolving trade dynamics around carbon conditionality.

Governments must address critical data deficiencies and enhance transparency across both established and emerging trade routes.
Currently, there is a notable lack of reliable, timely and transparent data pertaining to cross-border trade in electricity and clean fuels. Establishing robust certification, standards, and transparency mechanisms for these emerging trade avenues is essential. These measures are crucial not only for ensuring energy security but also for facilitating accurate carbon accounting. Moreover, countries must regularly forecast and manage their future energy import requirements. Transparent and periodic forecasting of anticipated import demands can smooth the transition by providing clarity and direction to both domestic and international stakeholders and investors. This approach benefits participants in traditional fossil fuel supply chains as well as those in the evolving energy transition value chains.

Policy makers need to establish robust governance and security frameworks to detect and mitigate threats to energy systems in the transitional phase.
Recent disruptions have highlighted the susceptibility of energy systems to accidents, natural disasters and malicious actions. Critical energy infrastructure is vulnerable to a variety of threats, including cyberattacks, security breaches and extreme weather events. Measures to enhance resilience in the face of disruptions are essential; they should fully integrate demand-side response measures, such as fuel switching and demand-reduction policies. International co-ordination of detection, protection and contingency plans, along with close co-operation with the private sector, can enhance the effectiveness of such measures.

© pixdeluxe; iStock

REFERENCES

ACER (2024), *Key developments in EU electricity wholesale markets*, https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_2024_MMR_Key_developments_electricity.pdf

Babayomi, O. O., *et al.* (2022), "Affordable clean energy transition in developing countries: Pathways and technologies", *iScience*, vol. 25/5, pp. 104178, https://doi.org/10.1016/j.isci.2022.104178

Bakare, M. S., et al. (2023), "A comprehensive overview on demand side energy management towards smart grids: challenges, solutions, and future direction", *Energy Informatics*, vol. 6/1, pp. 4, https://doi.org/10.1186/s42162-023-00262-7

Bento, N., *et al.* (2024), "Leverage demand-side policies for energy security", *Science*, vol. 383/6686, pp. 946–9, https://doi.org/10.1126/science.adj6150

Bing, C., and Kelly, S. (2021), "Cyber attack shuts down U.S. fuel pipeline 'jugular,' Biden briefed", https://www.reuters.com/technology/colonial-pipeline-halts-all-pipeline-operations-after-cybersecurity-attack-2021-05-08/

Bordoff, J., and O'Sullivan, M. L. (2021), "Green Upheaval: The New Geopolitics of Energy", https://www.foreignaffairs.com/articles/world/2021-11-30/geopolitics-energy-green-upheaval

Brinkerink, M., *et al.* (2024), "Global Transmission Database", [object Object], https://doi.org/10.5281/ZENODO.10063445

Carfora, A., *et al.* (2022), "Forecasting the COVID-19 effects on energy poverty across EU member states", *Energy Policy*, vol. 161, pp. 112597, https://doi.org/10.1016/j.enpol.2021.112597

Cembalest, M. (2024), *Eye of the Market*, https://assets.jpmprivatebank.com/content/dam/jpm-pb-aem/global/en/documents/eotm/electravision.pdf#page=31

Cheng, A. L., *et al.* (2024), "Electric vehicle battery chemistry affects supply chain disruption vulnerabilities", *Nature Communications*, vol. 15/1, pp. 2143, https://doi.org/10.1038/s41467-024-46418-1

Cherp, A. and Jewell, J. (2013), "International Handbook of Energy Security", https://doi.org/10.4337/9781781007907.00018

Climate Impact Lab (2023), "Climate Impact Map", https://impactlab.org/map/#usmeas=absolute&usyear=1986-2005&gmeas=absolute&gyear=2020-2039&tab=global

EEAS (2020), Climate Change and Defence Roadmap, https://climate-laws.org/documents/climate-change-and-defence-roadmap-eeas-2020-1251_c107?id=climate-change-and-defence-roadmap-eeas-2020-1251_2140

Ember (2024a), "Yearly electricity data", https://ember-climate.org/data-catalogue/yearly-electricity-data/

Ember (2024b), "European Electricity Review 2024", https://ember-climate.org/insights/research/european-electricity-review-2024/

Energy Institute (2023), "Statistical Review of World Energy", https://www.energyinst.org/statistical-review

Erbach, G., and O'Shea, J. (2019), *Cybersecurity of critical energy infrastructure*, https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/642274/EPRS_BRI(2019)642274_EN.pdf

Eurelectric (2022), *The coming storm: Building electricity resilience to extreme weather*, Eurelectric, Brussels, https://resilience.eurelectric.org/ (accessed 13 April 2024).

European Commission (2022), *Communication from the Commission to the European parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*, https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Commission (2023a), "Hybrid threats: a Comprehensive Resilience Ecosystem.", Publications Office, LU, https://data.europa.eu/doi/10.2760/37899 (accessed 6 April 2024).

European Commission (2023b), "Fortifying defence: strengthening critical energy infrastructure against hybrid threats.", Publications Office, LU, https://data.europa.eu/doi/10.2760/58406 (accessed 6 April 2024).

FAO (1997), *RWEDP Report No.33*, https://wgbis.ces.iisc.ac.in/energy/HC270799/RWEDP/acrobat/rm33.pdf

Faruqui, A., and Sergici, S. (2010), "Household response to dynamic pricing of electricity: a survey of 15 experiments", *Journal of Regulatory Economics*, vol. 38/2, pp. 193–225, https://doi.org/10.1007/s11149-010-9127-y

Fearn, N. (2024), "Industrial and energy groups warned of need for stronger cyber defence", https://www.ft.com/content/b8efa4ba-f5b9-46b1-94e4-e1620aa58e06

Fischhendler, I., *et al.* (2016), "The geopolitics of cross-border electricity grids: The Israeli-Arab case", *Energy Policy*, vol. 98, pp. 533–43, https://doi.org/10.1016/j.enpol.2016.09.012

Gielen, D., *et al.* (2019), "The role of renewable energy in the global energy transformation", *Energy Strategy Reviews*, vol. 24, pp. 38–50, https://doi.org/10.1016/j.esr.2019.01.006

Global Commission on the Geopolitics of Energy Transformation (2019), *A New World: The Geopolitics of the Energy Transformation*, IRENA, Federal Foreign Office Germany, Norwegian Ministry of Foreign Affairs and UAE Ministry of Energy and Industry, Abu Dhabi, https://www.irena.org/publications/2019/Jan/A-New-World-The-Geopolitics-of-the-Energy-Transformation (accessed 14 April 2024).

Guo, F., *et al.* (2022), "Implications of intercontinental renewable electricity trade for energy systems and emissions", *Nature Energy*, vol. 7/12, pp. 1144–56, https://doi.org/10.1038/s41560-022-01136-0

IAEA (n.d), *The Nuclear Fuel Cycle*, https://www.iaea.org/sites/default/files/19/02/the-nuclear-fuel-cycle.pdf

IBM (2024), *IBM X-Force Threat Intelligence Index 2024*, https://www.ibm.com/reports/threat-intelligence

IEA (2022a), *Climate Resilience for Energy Security*, IEA, Paris, https://iea.blob.core.windows.net/assets/10229b31-fd82-4371-b92c-a554f95369ea/ClimateResilienceforEnergySecurity.pdf (accessed 29 March 2023).

IEA (2022b), *Climate Resilience for Energy Security*, https://iea.blob.core.windows.net/assets/10229b31-fd82-4371-b92c-a554f95369ea/ClimateResilienceforEnergySecurity.pdf

IEA, *et al.* (2023), *Tracking SDG7: The energy progress report 2023*, International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, the World Bank and World Health Organization, Geneva, www.irena.org/Publications/2023/Jun/Tracking-SDG7-2023

IEA (2023a), "International Shipping", https://www.iea.org/energy-system/transport/international-shipping

IEA (2023b), "Hydrogen Production and Infrastructure Projects Database", https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database

IEA (2023c), "Emergency response and energy security", https://www.iea.org/about/emergency-response-and-energy-security (accessed 14 April 2024).

IRENA (2009), *Statute of IRENA signed in Bonn*, https://www.irena.org/-/media/Irena/Files/Official-documents/IRENA-Statute/IRENAstatuteenIRENAFCStatutesignedinBonn26012009incldeclarationonfurtherauthenticversions.pdf?rev=d619033053354d20884bde3aef72224f

IRENA (2016), *Renewable Energy Benefits: Decentralised solutions in the agri-food chain*, International Renewable Energy Agency, https://www.irena.org/publications/2016/Sep/Renewable-Energy-Benefits-Decentralised-solutions-in-agri-food-chain

IRENA (2017a), *Renewable energy benefits: Leveraging local capacity for solar PV*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2017/Jun/Renewable-Energy-Benefits-Leveraging-Local-Capacity-for-Solar-PV

IRENA (2017b), *REthinking energy: Accelerating the global energy transformation*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/publications/2017/Jan/REthinking-Energy-2017-Accelerating-the-global-energy-transformation

IRENA (2018a), *Power system flexibility for the energy transition*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition

IRENA (2018b), *Power system flexibility for the energy transition – Part I: Overview for policy-makers*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf (accessed 16 December 2022).

IRENA (2019), *Innovation landscape for a renewable-powered-future*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future (accessed 5 March 2020).

IRENA (2020a), *Global renewables outlook: Energy transformation 2050*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

IRENA (2021a), *The Renewable Energy Transition in Africa*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/publications/2021/March/The-Renewable-Energy-Transition-in-Africa

IRENA (2021b), *Bracing for climate impact: Renewables as a climate change adaptation strategie*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2021/Aug/Bracing-for-climate-impact-2021

IRENA (2022a), *Geopolitics of the energy transformation: The hydrogen factor*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

IRENA (2023a), *Geopolitics of the energy transition: Critical materials*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jul/Geopolitics-of-the-Energy-Transition-Critical-Materials

IRENA (2023b), *World Energy Transitions Outlook 2023: 1.5°C Pathway*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023

IRENA, *et al.* (2023), *Tracking SDG7: The energy progress report 2023*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/Publications/2023/Jun/Tracking-SDG7-2023

IRENA (2024a), *Tracking COP28 outcomes: Tripling renewable capacity by 2030*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/Publications/2024/Mar/Tracking-COP28-outcomes-Tripling-renewable-power-capacity-by-2030 (accessed 17 June 2020).

IRENA (2024b), *Renewable capacity statistics,* International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024

IRENA (2024c), "Global Atlas for Renewable Energy", International Renewable Energy Agency, Abu Dhabi, https://globalatlas.irena.org/workspace

IRENA (2024d), *Green hydrogen for sustainable industrial development: A policy toolkit for developing countries*, International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/Publications/2024/Feb/Green-hydrogen-for-sustainable-industrial-development-A-policy-toolkit-for-developing-countries

IRENA (2024e), "Systemic Changes Needed to Triple Renewables by 2030", International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/Digital-content/Digital-Story/2024/Mar/Systemic-Changes-Needed-to-Triple-Renewables-by-2030/detail (accessed 26 March 2024).

IRENA (2024f), "RE Technology Patent Reports", International Renewable Energy Agency, Abu Dhabi, https://inspire.irena.org/Pages/patents/Patents-Search.aspx

ISS (2023), "Cybersecurity Threats to Critical Energy Infrastructure: Business Continuity in a Changing Geopolitical Environment", https://insights.issgovernance.com/posts/cybersecurity-threats-to-critical-energy-infrastructure-business-continuity-in-a-changing-geopolitical-environment/ (accessed 26 March 2024).

Jack, V. (2023), "Europe's grid is under a cyberattack deluge, industry warns", https://www.politico.eu/article/energy-power-europe-grid-is-under-a-cyberattack-deluge-industry-warns/

KonBriefing (2023), "Worldwide cyber incidents, data breaches, ransomware", https://konbriefing.com/en-topics/cyber-attacks-2023-ind-energy-industry.html

Le Monde (2022), "Norway considers suspending electricity exports to avoid an energy crisis", https://www.lemonde.fr/en/international/article/2022/08/20/norway-considers-suspending-electricity-exports-to-avoid-an-energy-crisis_5994226_4.html

Lilliestam, J., and Ellenbeck, S. (2011), "Energy security and renewable electricity trade – Will Desertec make Europe vulnerable to the 'energy weapon'?", *Energy Policy*, vol. 39/6, pp. 3380–91, https://doi.org/10.1016/j.enpol.2011.03.035

Nakashima, E., *et al.* (2021), "Ransomware attack leads to shutdown of major U.S. pipeline system", https://www.washingtonpost.com/business/2021/05/08/cyber-attack-colonial-pipeline/

Noronha, L. (2012), *Energy anf Resource Security - Towards an inclusive and positive agenda*, The Energy Resource Institute (TERI) and Konrad Adenauer Stiftung (KAS), New Delhi, https://www.kas.de/documents/252038/253252/7_dokument_dok_pdf_33377_1.pdf/2f6b5008-6a0c-c513-2c58-43ccbb685b19?version=1.0&t=1539663400635 (accessed 14 April 2024).

Our World in Data (2023), "Yearly Electricity Data, 2023", based on Ember (2022), European Electricity Review, https://ourworldindata.org/energy

Paust, J. J., and Blaustein, A. P. (1974), "The Arab Oil Weapon—A Threat to International Peace", *American Journal of International Law*, vol. 68/3, pp. 410–39, https://doi.org/10.2307/2200513

Perera, A. T. D., *et al.* (2020), "Quantifying the impacts of climate change and extreme climate events on energy systems", *Nature Energy*, vol. 5/2, pp. 150–9, https://doi.org/10.1038/s41560-020-0558-0

Power Technology (2020), "The world's longest power transmission lines", https://www.power-technology.com/features/featurethe-worlds-longest-power-transmission-lines-4167964/?cf-view

Reuters (2022), "Russia cuts power exports to Finland over failed payments", https://www.reuters.com/markets/europe/russia-cuts-power-exports-finland-over-failed-payments-2022-05-16/

Rügamer, A., *et al.* (2015), "Jamming and Spoofing of GNSS Signals – An Underestimated Risk?!", https://www.fig.net/resources/proceedings/fig_proceedings/fig2015/papers/ts05g/TS05G_ruegamer_kowalewski_7486.pdf

Schneider, M., and Froggatt, A. (2023), *World Nuclear Industry Status Report 2023*, https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2023-.html

Scott, D. (2024), "Frigid temps cut US natural gas supply as demand soars, Texas faces possible shortfall", https://www.reuters.com/business/energy/frigid-temps-cut-us-natgas-supply-demand-soars-texas-faces-possible-shortfall-2024-01-14/

Sharmina, M., *et al.* (2017), "Global energy scenarios and their implications for future shipped trade", *Marine Policy*, vol. 84, pp. 12–21, https://doi.org/10.1016/j.marpol.2017.06.025

Stupp, C. (2022), "European Wind-Energy Sector Hit in Wave of Hacks", https://www.wsj.com/articles/european-wind-energy-sector-hit-in-wave-of-hacks-11650879000

Subramanian, S. (2022), "Forty percent of all shipping cargo consists of fossil fuels", https://qz.com/2113243/forty-percent-of-all-shipping-cargo-consists-of-fossil-fuels.

Tainturier, B. (2020), "To Explain, to Understand, or to Tell the Gilets Jaunes?", https://www.europenowjournal.org/2020/01/15/11569/

The Guardian (2018), "How hi-vis yellow vest became symbol of protest beyond France", https://www.theguardian.com/world/2018/dec/21/how-hi-vis-yellow-vest-became-symbol-of-protest-beyond-france-gilets-jaunes

TransitionZero (2023), *Cables to change the world*, https://www.transitionzero.org/insights/interconnector-report-feo

UN Comtrade Database (2022), "Trade Data", https://comtradeplus.un.org/TradeFlow

UNCTAD (2022), *Review of Maritime Transport*, https://unctad.org/system/files/official-document/rmt2022ch1_en.pdf

UNCTAD (2024), "Unprecedented shipping disruptions raise risk to global trade, UNCTAD warns", https://unctad.org/news/unprecedented-shipping-disruptions-raise-risk-global-trade-unctad-warns

UNEP (2023), *Global Climate Litigation Report*, https://wedocs.unep.org/bitstream/handle/20.500.11822/43008/global_climate_litigation_report_2023.pdf?sequence=3

United Nations (2012), *UN General Assembly resolution 66/290*, https://www.un.org/humansecurity/wp-content/uploads/2022/06/N1147622.pdf

United Nations Office for Disaster Risk Reduction (2022), *Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future*, United Nations Office for Disaster Risk Reduction, Geneva, https://www.undrr.org/media/79595/download?startDownload=true (accessed 14 April 2024).

Van de Graaf, T. and Sovacool, B.K. (2020), "Global energy politics", *Polity*, Cambridge, UK ; Medford, MA.

Walsh, C., *et al.* (2019), "Trade and trade-offs: Shipping in changing climates", *Marine Policy*, vol. 106, pp. 103537, https://doi.org/10.1016/j.marpol.2019.103537

WHO, *et al.* (2023), *Energizing health: Accelerating electricity access in health-care facilities*, World Health Organization, Geneva, International Renewable Energy Agency, The World Bank and Sustainable Energy For All, www.irena.org/Publications/2023/Jan/Energizing-health-accelerating-electricity-access-in-health-care-facilities

Wiggel, M., *et al.* (2021), *Best practices in the whole-of-society approach in countering hybrid threats.*, Publications Office, LU, https://data.europa.eu/doi/10.2861/702047 (accessed 6 April 2024).

WIPO (2015), "WIPO Expert Forum on International Technology Transfer", https://www.wipo.int/pressroom/en/stories/int_tech_transfer.html

WMO (2022), *State of Climate Services*, https://library.wmo.int/viewer/58116/download?file=1301_WMO_Climate_services_Energy_en.pdf&type=pdf&navigator=1

WNISR (2023), *World Nuclear Industry Status Report*, https://www.worldnuclearreport.org/Nuclear-Reactor-Construction-Starts-Drop-Again-in-the-World.html

World Nuclear Association (2017), "Military Warheads as a Source of Nuclear Fuel", https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/military-warheads-as-a-source-of-nuclear-fuel.aspx

World Nuclear Association (2022), *Uranium Enrichment*, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx

World Nuclear Association (2023a), "Supply of Uranium", https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx

World Nuclear Association (2023b), *High-assay low-enriched uranium (HALEU)*, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/high-assay-low-enriched-uranium-(haleu).aspx

Wright, I. (2023), "Every Country's Top Export and Import", https://businessfinancing.co.uk/top-export-and-import/

Yalew, S. G., *et al.* (2020), "Impacts of climate change on energy systems in global and regional scenarios", *Nature Energy*, vol. 5/10, pp. 794–802, https://doi.org/10.1038/s41560-020-0664-z

Zachmann, G. (2023), "The great 2022 European energy crisis - what actually happened and how did Europe cope?", https://www.bruegel.org/newsletter/great-2022-european-energy-crisis-what-actually-happened-and-how-did-europe-cope-0

IRENA
International Renewable Energy Agency

www.irena.org