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中国机电产品进出口商会
China Chamber of Commerce for Import and
Export of Machinery and Electronic Products

RENEWABLE ENERGY AND ENERGY SECURITY

AN INDUSTRY PERSPECTIVE

CONTENTS

ABBREVIATION

	English full form
AI	Artificial Intelligence
APERC	Asia Pacific Energy Research Centre
API	Application Programming Interface
AWS	Amazon Web Services
BYD	BYD Company Limited
CATL	Contemporary Amperex Technology Co., Limited
CSR	Corporate Social Responsibility
EIA	U.S. Energy Information Administration
ESG	Environmental, Social and Governance
ETS	Emissions Trading System
EUR	Euro
EV	Electric Vehicle
FAO	Food and Agriculture Organization (of the United Nations)
GCC	Gulf Cooperation Council
GHG	Greenhouse Gas
GW	Gigawatt
GWh	Gigawatt-hour
IEA	International Energy Agency
IoT	Internet of Things
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour
LCOE	Levelized Cost of Energy
MEE	Ministry of Ecology and Environment (China)
MW	Megawatt
MWh	Megawatt-hour
PPA	Power Purchase Agreement
PV	Photovoltaic
RFEG	Road Freight Electrification Guidance
SDG7	Sustainable Development Goal 7 (Affordable and Clean Energy)
TWh	Terawatt-hour
TW	Terawatt
UNECE	United Nations Economic Commission for Europe
USTR	United States Trade Representative
USD	United States Dollar

FOREWORD

Energy security is a central concern of modern society. Recent shocks have shown how deeply energy affects daily life and economic confidence. Price volatility can quickly become a public concern. Disrupted supplies can slow investment. Weak infrastructure can turn moderate pressures into crises. Climate change adds another layer of risk, as heat, storms, and drought place greater stress on energy systems.

Renewable energy has a clear role in addressing these challenges. It gives countries more options for secure power supplies and helps reduce exposure to imported fuels. It fosters energy resilience and security on three levels: at the national level through reduced fossil fuel imports; at the grid level through a more resilient, distributed network; and at the household and building level through rooftop solar and behind the meter battery storage that enables families and infrastructure to withstand exogenous shocks. Renewables also support local development when projects are well connected to grids and communities, and they strengthen long term resilience when deployed with storage, digitalisation, and flexible markets. These contributions matter for all economies, whether they are expanding access to electricity or adjusting energy systems for a low carbon future.

The Global Solar Council sees this as a practical task. Renewable capacity must grow, and it must be turned into dependable energy services through well-equipped infrastructure, reasonable market design, responsible supply chain management, and projects that meet sustainability and legitimacy standards. This is where industry experience becomes essential. Companies bring real-world knowledge from projects in many regions. They understand where deployment is delayed and where costs rise. Industry associations can turn that experience into useful guidance for policy makers and support cooperation across markets where shared standards are needed.

This white paper is a welcome contribution to that effort. It looks at energy security from the perspective of the renewable energy industry's final consumers. It explains how renewable energy can strengthen resilience and lower vulnerability, while recognizing the constraints that still need to be addressed. We hope it helps decision makers move from ambition to delivery and supports a more secure energy future for all.

Sonia Dunlop
CEO, Global Solar Council
June 2026

Energy is the foundation of economic and social development and is vital to national development, people's livelihoods, and a sustainable global future. Today, geopolitical conflicts, extreme weather, and supply chain disruptions are compounding one another. Traditional energy security risks coexist with the mission of green and low-carbon transition. Accelerating renewable energy development and building a clean, low-carbon, secure, and efficient energy system have become a shared priority for countries seeking to address climate change and strengthen development resilience.

China has been a steadfast driver of the global energy transition. China's machinery and electronic products industry has developed a complete supporting system in solar photovoltaics, wind power, energy storage, new energy vehicles, and key equipment, providing solid support for global clean energy deployment through reliable, efficient, and affordable solutions. As the national industry organization for foreign trade and economic cooperation in machinery and electronic products, the China Chamber of Commerce for Import and Export of Machinery and Electronic Products (CCCME) has long believed that a fair, open, and stable trade environment, alongside coordination and mutual trust across industrial and supply chains, forms the foundation of global energy security.

At the same time, the global energy transition still faces multiple challenges, including grid connection, system flexibility, critical mineral supplies, green trade rules, and carbon footprint accounting. Only by upholding openness, inclusiveness, and mutually beneficial cooperation can industries worldwide join forces to address uncertainties in the transition.

From an industry perspective, this white paper explores the relationship between renewable energy and energy security and offers constructive recommendations. CCCME stands ready to work with global industry peers to build consensus and jointly advance a safer, greener, and more inclusive energy future.

Shi Yonghong
Vice President, CCCME
June 2026

EXECUTIVE SUMMARY

Throughout human history, evolving energy use has contributed to nearly every pivotal transformation. From the primitive gathering of firewood, to industrial revolutions driven by steam and internal combustion, and finally to the electro-tech era, the transformation of energy flows has fundamentally shaped the material cycle of the biosphere, human social organization, and governance structures (Lenton, Pichler, & Weisz 2016). Today, the functioning of modern economies relies heavily on large-scale and stable energy supply, as energy remains a prerequisite for industrial production, transport, communication, digital services, and decent living conditions (IEA 2024; Cheng et al. 2025). Energy security has therefore become a crucial factor for development at both macro and micro levels.

Despite its critical importance, energy security is constrained by a series of issues that are usually out of effective control. Such issues include imbalanced distribution and finite reserves of major fuels, financial volatility, geopolitical tensions and conflicts, extreme weather events, as well as the structural adjustment of energy use and associated impact (Gitelman, Magaril, & Kozhevnikov 2023).

Traditional fossil fuels, as compared to renewable energy, are more likely to be exposed to the negative impact of above-mentioned factors, while dependence on them in turn will exacerbate the influences of these factors. In contrast, renewable energy provides an alternative pathway by diversifying the energy structure and reducing reliance on fuel routes that are geographically concentrated or politically unstable (IRENA 2024). Its relevance is also expanding as critical sectors such as digital infrastructure, transport and logistics, mining, and agri-food systems require cleaner and more reliable energy services.

However, expanding renewable capacity as much as possible is not a prudent strategy for energy security. Recent supply failures show that energy systems can remain vulnerable even when clean-energy assets are present.

Renewable facilities need to be embedded in the institutions and infrastructure through which energy is delivered, financed, traded, and accepted by society.

This report therefore understands the role of the renewable energy industry as a process of multi-layered economic resilience. The contribution lies in turning dispersed natural resources and industrial capabilities into energy services that reduce vulnerability and increase resilience across the wider system. From this perspective, renewable energy security depends not only on production and trade, but also on whether clean-energy products can sustain everyday services, support key economic functions, withstand climate impacts, maintain responsible supply chains, and retain social trust.

Such contribution is also constrained by the conditions under which the energy transition takes place. Reducing fossil-fuel dependence shifts attention toward the material and industrial base behind clean-energy technologies. A power system with high renewable penetration must be able to manage variability in a flexible manner. without allowing congestion, curtailment or extreme weather to impact energy system services. Financing conditions and market rules determine whether enterprises have sufficient incentives to invest in flexibility and long-term system value. International rules also matter because fragmented carbon accounting and trade measures can raise costs and restrict the flow of clean-energy technologies. At the local level, projects that fail to respect land, water, and community interests may lose legitimacy and become sources of delay or conflict.

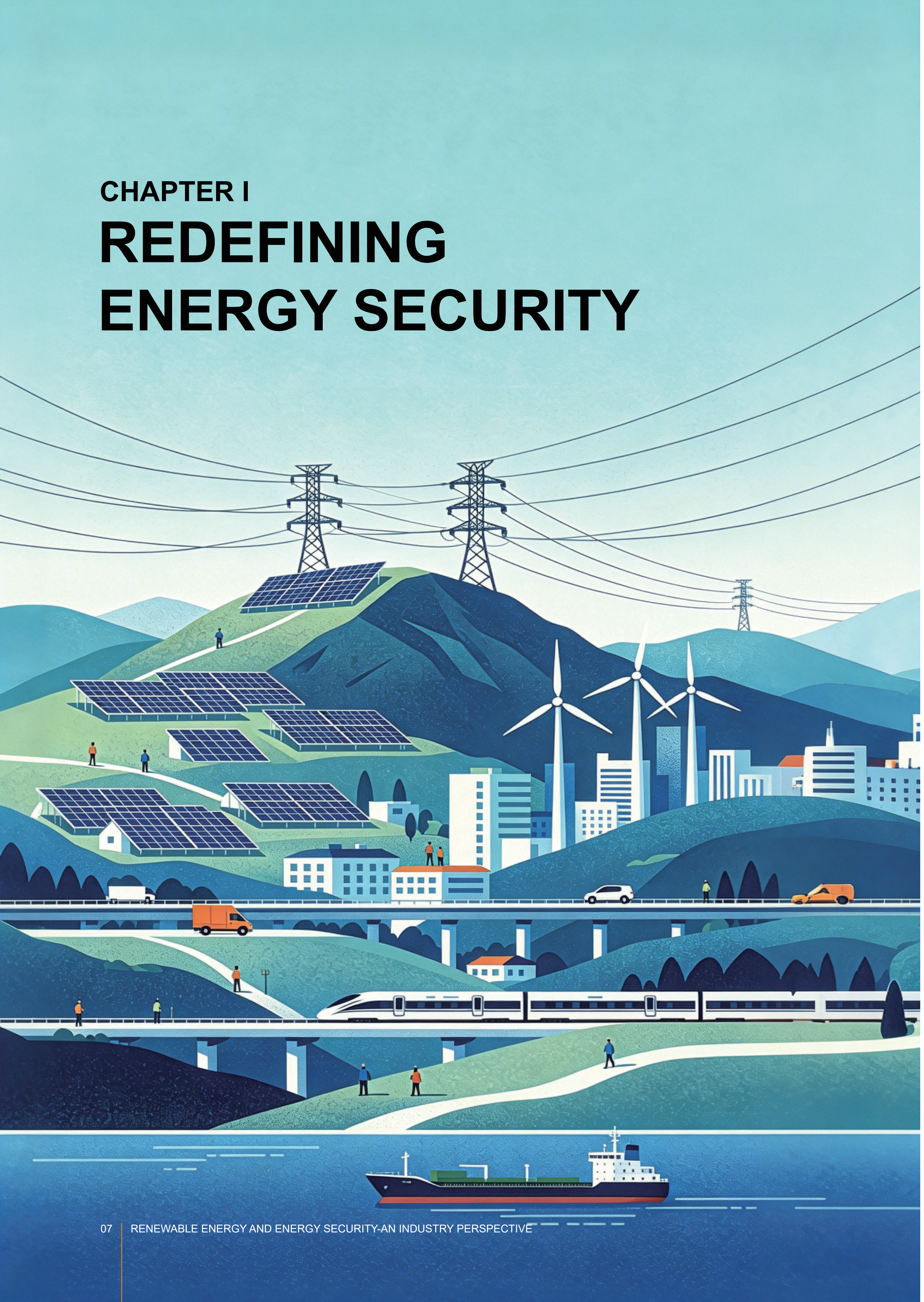
For these reasons, strengthening energy security requires more than replacing fossil fuels with renewable technologies. It requires grid-centered renewable energy deployment, commercially investable flexibility, responsible management of critical materials, open trade rules that maximize global deployment, and stronger social license for renewable projects.

Renewable energy is not an end goal in and of itself but an essential pillar in the electro-tech transition of the wider economy, which cannot stand alone unless it is supported by resilient infrastructure, diversified supply chains, and effective governance arrangements.

This report is structured as follows. Chapter I redefines energy security from the perspective of the renewable energy industry by applying the questions of “for whom”, “for which values” and “for what threat”. Chapter II examines how the industry contributes to energy security through supply diversification, critical-sector support, climate mitigation, system resilience and responsible supply chain transformation. Chapter III analyzes the major constraints that may weaken this contribution. Chapter IV then proposes policy recommendations for building the enabling conditions under which renewable energy can contribute more effectively to long-term security and sustainable development.

CHAPTER I

REDEFINING ENERGY SECURITY



People have not reached a universal consensus on the definition of energy security until today. In the classic notion shaped by the oil shocks of 1970s-1980s that caused widespread disruption, the central concern was whether sufficient energy resources, namely fossil fuels, could be provided at a tolerable price, which is still able to describe part of the core meanings of energy security. Yet, as the trendy issues of interests are constantly changing due to the shifting historical context, such definition is no longer adequate on its own (Ang, Choong, & Ng 2015). Nowadays a commonly-used discourse of energy security is the four As - availability, affordability, accessibility and acceptability (Cherp & Jewell 2014). Such narrative covers the afore-mentioned concept, and expands it with growing attention to environmental sustainability and energy efficiency (APERC 2007). Dozens of articles have referred to APERC's opinion directly or come up with similar interpretation, making the four As almost an intrinsic characteristic of energy security.

However, Cherp and Jewell (2014) proposed, from another angle, that the four As mainly answer the characteristics of energy systems and fail to provide a people-centered perspective.

> **They argue that to tackle the real core of energy security, three questions need to be solved: "Energy security for whom? For which values? For what threat?" On this basis, they suggest defining energy security as the "low vulnerability of vital energy systems".**

Nevertheless, rather than creating a unified and rigid concept, they also call for leaving inclusive spaces of bringing in factors under different objective conditions and subjective considerations of various stakeholders. For this report written for the renewable energy industry, such framing is useful because it clarifies what kind of "energy security" the industry is actually concerned with. The industry is not only a supplier of alternative fuels in the classical sense but increasingly a part of the infrastructure, technology base, and trade structure through which modern energy services are delivered. The three questions therefore function as a way to specify what energy security means for the renewable energy industry as actors in a transitioning system, before any discussion of concrete actions.

1.1

ENERGY SECURITY FOR WHOM?

Like companies in all other sectors, renewable energy corporations intrinsically seek profit growth, as maintaining profitability is one condition under which the firm can continue to invest, produce, deliver, and innovate, with acceptable quality assured. Therefore, the most immediate subject of energy security in this sector is the customer and the end-user who depend on clean energy products and services. If renewable energy becomes part of the vital energy system that Cherp and Jewell mentioned, then its security is judged not simply by whether a company can sell products, but by whether those products support reliable, affordable, and usable energy services for households, businesses, and public institutions.

However, due to the 'green' nature of the renewable energy sector and its unique position in pursuing sustainable development, the energy security of this industry is bound to expand beyond manufacturers' own balance sheets. Renewable energy value chains involve a wide range of actors, from raw-material suppliers and equipment manufacturers to project developers, recyclers, grid-service providers, and power plant operators. Their actions can affect the stability, cost, and legitimacy of the whole system, while a stable and effective supply chain is mutually necessary for all actors to function normally and securely (Yahyazadeh 2023). This interdependence can be seen in China-GCC renewable energy supply chains: although Gulf states may face dependence on Chinese solar panel and wind turbine manufacturers, strategic collaboration and market innovation have created possibilities for building more secure and resilient supply chains (Sim & Griffiths 2024, p. 9). Industry associations and councils also matter in this context because they can aggregate otherwise fragmented concerns into common positions on grid access, trade rules, sustainability standards, supply-chain resilience and social acceptance. Therefore, the subject of energy security expands from individual firms and end-users to the wider stakeholder network that makes clean-energy delivery possible.

Additionally, energy security for the renewable energy sector means more than keeping satisfying financial figures or creating a good commercial atmosphere, it also stands as a part of corporate social responsibility (CSR). Vagin et al. (2022) directly interpret the CSR of energy companies as their voluntary activities undertaken to fulfill the SDG7: "ensure access to affordable, reliable, sustainable and modern energy for all". Among the major factors in SDG7 narrative, 'affordable' and 'reliable' can be regarded as an energy justice issue that promotes people-centered perspective, which focuses more on ordinary and low-income population's access to sufficient energy with reasonable price. To address such issue, appealing to corporations to undertake their social responsibility serve as an effective catalyst (Batool et al. 2023). The 'sustainable' and 'modern' part of SDG7 then calls for a climate and environment friendly energy transition, a process which renewable energy will certainly contribute to due to its nature. These linkages with CSR direct the energy security for renewable energy enterprises towards broader social aspects.

Thus, for the renewable energy sector, the answer to 'energy security for whom' becomes clear. It is for the whole stakeholder network whose access to clean, reliable, and socially acceptable energy depends on the functioning of renewable energy value chains.

1.2

ENERGY SECURITY FOR WHICH VALUES?

If the question "energy security for whom" clarifies the stakeholders relevant with the whole renewable energy industry, then "energy security for which values", further asks what exactly is worth protecting. As Cherp and Jewell (2014) argue, the four As are only characteristics of energy systems, rather than human or social values themselves. In their view, failing to identify protected values and their connections with energy means failing to answer the policy question of "which energy systems to protect". For the renewable energy industry, this reminder is important because the value of energy security cannot be reduced to the physical existence of energy resources or the commercial success of a single company. It should be understood through the social, economic, and environmental values that renewable energy systems are expected to support.

The first value remains the stable provision of usable and affordable energy services. Energy security of renewable energy industry does not only mean that products are produced and traded, but that they can be converted into energy services to meet the requirement of critical social functions, economic activities, as well as human well-being (Bento et al. 2024). Such demand-side perspective offers a strong complement to the policy-centered and supply-focused understanding of energy security (Bento et al. 2024). Changing dynamics between supply and demand side always create new forms of vulnerability in energy systems.

In 2nd March, 2026, AWS data center experienced drone strikes due to the geopolitical conflict. The explosion resulted in a forced cutoff of power supply, impacting millions of global cloud services users. Despite the disruption of Claude.ai, API, and Claude code for civilian use, Claude for Government remains in operation due to independent energy source, demonstrating the imbalance between ordinary people and the privileged under this new circumstance of energy security. Therefore, talking about the industrial role in the new era never means to abandon the value of availability and affordability, but to keep them in a more service-oriented direction. Such direction is exactly where enterprises' strengths lie.

Climate change and environmental impact mitigation is an indispensable theme of our time. This theme ties the legitimacy of renewable energy sector to its contribution to a low-carbon transition, and also provides unprecedented opportunities of development.

Numerous studies highlight that the utilization of fossil fuel have led to adverse impact on climate change and environment, as over three quarters of total GHG emissions and more than 95% of CO2 emissions come from fossil fuel use (Ge, Friedrich, & Vigna 2026).

Under this condition, renewable energy becomes one of the most effective alternatives to meet the increasing energy demand, with indisputable potential in lower GHG emissions (Owusu & Asumadu-Sarkodie 2016; Attanayake et al. 2024). However, the climate and environmental impact can also affect the production and use of renewable energy facilities. For example, high waves can pose threat to offshore wind farm or solar panel, severe drought can generate significant influence on biomass based energy, while extreme weather phenomena impose a high risk level on nearly all types of renewable energy (Girgibo et al. 2024). In this sense, what renewable energy security stands for is to protect the possibility of meeting energy demand without deteriorating the environmental vulnerabilities, and reducing overall risk level of climate and environmental impact, whether caused by human activities or not.

Resilience across the clean energy value chain also matters. A renewable energy system can only protect social and environmental values if the technologies, materials, infrastructure, and trade networks behind it remain functional. This is why the value of energy security for this sector also includes technological reliability, industrial continuity, and supply-chain resilience. Mertens et al. (2024) point out that the large-scale deployment of clean energy technologies creates rapidly growing demand for critical raw materials, and that sustainable access to these materials is crucial for the clean energy transition while taking environmental and social impacts into consideration. Therefore, energy security for the renewable energy industry also includes the stability and responsibility of both the upstream and midstream stakeholders along the supply chain that allow renewable energy to be delivered at scale. Moreover, not every renewable project or product is automatically socially acceptable. Their development still requires consideration on land use, mining, and community, linking broader population to renewable energy project or product in a more direct way. Thus, energy security in the renewable sector must protect not only technical performance, but also fairness, trust, and responsibility in the way energy benefits and burdens are distributed.

1.3

ENERGY SECURITY FOR WHAT THREAT?

As section IV will analyze the threat and obstacle facing by renewable energy system in detail, this sub-section will only provide a general definition on the threat that a secured renewable energy system needs to tackle. Classic notions on energy security are usually focused on disruption events and the reason behind, while a series of academic materials “expanded the focus from the causes of disruptions to the ability to respond them” (Cherp & Jewell 2014, p. 418).

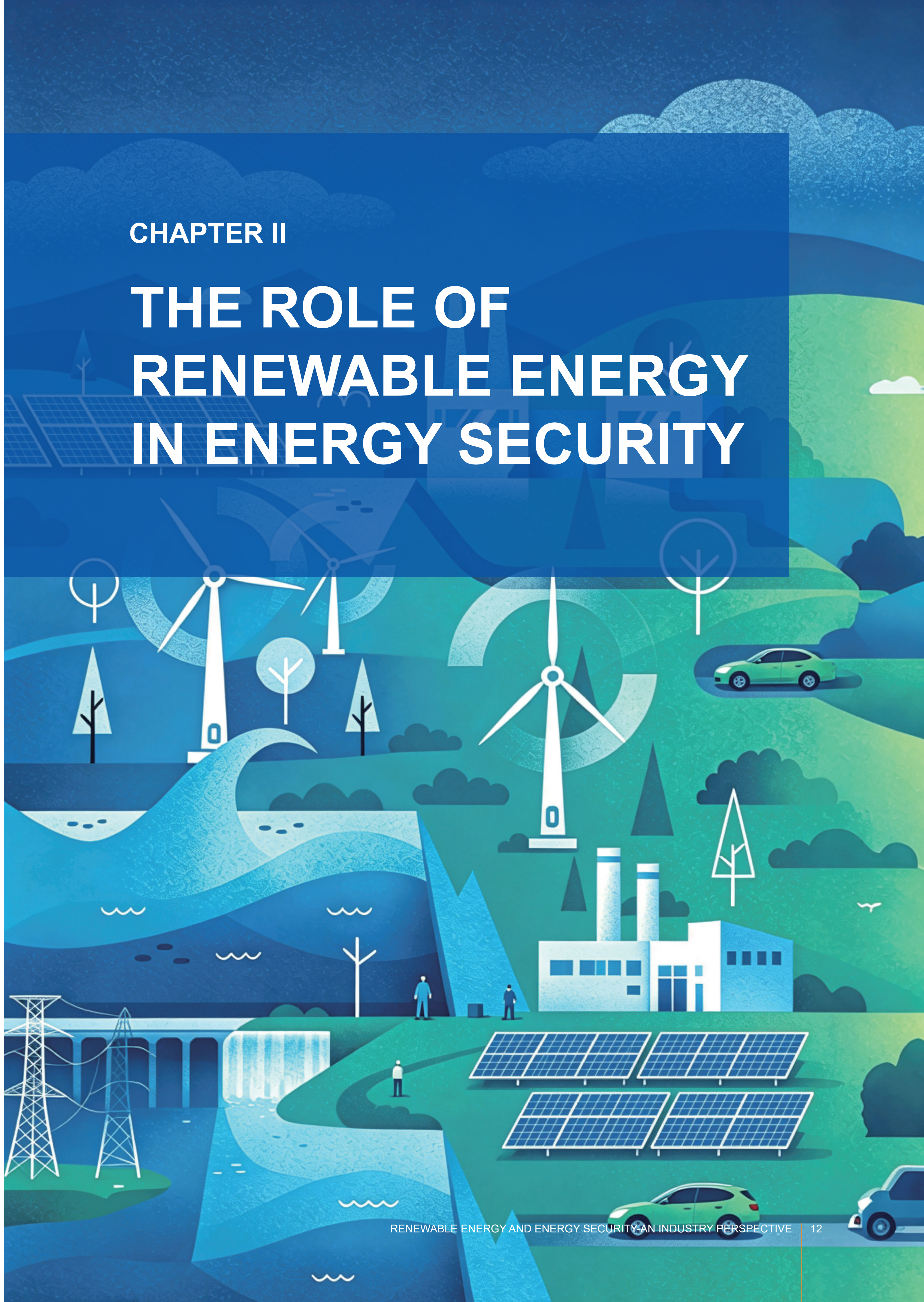
> **From this point of view, a structural measure to identify the threats is to divide them into two central categories: threats that impose vulnerabilities on the energy supply system, and threats that deteriorate the resilience of the system.**

The development of renewable energy system contributes to addressing and mitigating these threats, while the dynamics of these threats also influence the pattern of renewable energy.

In summary, applying the three-question framework to the renewable energy sector yields a clear and actionable definition of energy security. From the perspective of renewable energy industry, energy security is the low vulnerability of the vital energy system shaped by their products and services, directed towards the entire stakeholder network—from upstream and downstream supply chain partners to end-users and the communities affected by the industry’s activity. This security is realized not merely through the physical supply of alternative fuels, but by meeting service-oriented energy needs reliably and affordably, actively mitigating climate change and environmental degradation, stabilizing the supply chains and social environments in which the industry operates, and continuously strengthening equity, trust, and accountability in the provision of energy. The ultimate goal of such security is to reduce the systemic weaknesses that threaten the continuous delivery of clean energy services, thereby enhancing the overall resilience of the energy system.

CHAPTER II

THE ROLE OF RENEWABLE ENERGY IN ENERGY SECURITY



As the Chapter I has proposed the definition of energy security aiming specifically at the renewable energy industry, this section will analyze how this sector can contribute to the fulfillment of such a concept. Various articles have discussed the contribution of renewable energy to energy security from different angles, including as a diversified and cost-effective source of energy supply, a redemptive measure for human-caused climate change and environmental impact, a factor that can potentially shape geopolitical relationships, or a transformative power (Farghali et al. 2023; Aslantürk & Kıprızlı 2020; Zywiołek, Wolniak, & Grebski 2025; Gielen et al. 2019; Cheng et al. 2025). Integrating these opinions with the industrial point of view, renewable energy strengthens security when actors are able to convert dispersed natural resources into reliable services, connect those services to critical sectors, reinforce system resilience under climate and technological shocks, and organize supply chains in a responsible and socially legitimate way.

Thus, this report understands the role of the renewable energy industry as a process of multi-layered economic resilience: coordinating technologies, infrastructure, markets, and stakeholder responsibilities so that renewable energy can reduce vulnerability and strengthen resilience across the wider energy system.

2.1

DIVERSIFYING ENERGY SUPPLY

Energy supply diversification is one of the most visible ways in which renewable energy contributes to energy security. For low energy producing countries, energy insecurity often appears as exposure to external price shocks, current-account pressure, and geopolitical uncertainty. In this context, Aslantürk and Kıprızlı (2020) argue that renewable energy can expand energy diversity, reduce dependence on imported fossil fuel, as well as risks related to insufficient and single supply structure. This argument is not limited to national policy. It also explains why renewable energy enterprises matters: it acts as the ‘inverter’ between national energy strategy and people’s livelihood by converting geographically dispersed resources such as sunlight, wind, hydropower, biomass and geothermal heat into energy services that are less tied to a single fuel route, supplier or geopolitical relationship. Meanwhile, industry associations can support such diversification by mapping deployment barriers, sharing best practices across markets, and helping governments understand how domestic renewable resources can be converted into investable projects.

For photovoltaic enterprises, this contribution is especially clear because solar resources are widely distributed and modular technologies can be deployed at different scales, from household rooftops to utility-scale power plants. JA provides one useful example. Its CEME1 project uses 480 MW of JA modules and, after grid connection, became Chile’s largest PV installation. The project is located in the Atacama Desert, where it faces a harsh environment marked by heat, strong ultraviolet exposure, wind, and sand. The project expected annual output is about **one billion kWh**, enough to serve roughly **400,000 households**, while avoiding around **280,000 tons of CO$_2$ emissions** per year. The case is therefore relevant not simply because it demonstrates international trade and cooperation, but because the project helps Chile turn a local solar resource into a substantial part of its clean electricity supply.

Nevertheless, it is not feasible to rely on renewable energy to eliminate dependence. Although decreasing reliance on fossil fuel from external sources can lead to an overall reduction in national trade risks for most countries, countries that lack certain types of critical materials are increasingly exposed to trade risks for electricity and transportation systems (Cheng et al. 2025). Such finding prevents an overly simple conclusion that renewables automatically equal energy independence. In order to overcome this concomitant reliance, renewable energy enterprises need to consider how to use less and re-use more, replace rare materials with abundant ones, and relocate the activities relevant with mining and manufacturing (Mertens et al. 2024). The specific constraints of dependence and its countermeasure will be discussed in detail in the next chapter. Mentioning dependence on other critical materials here is to emphasize that the supply diversification effect of the renewable energy sector has a condition, which is to strengthen its focus on technology innovation, supply-chain diversification, recycling, and responsible sourcing.

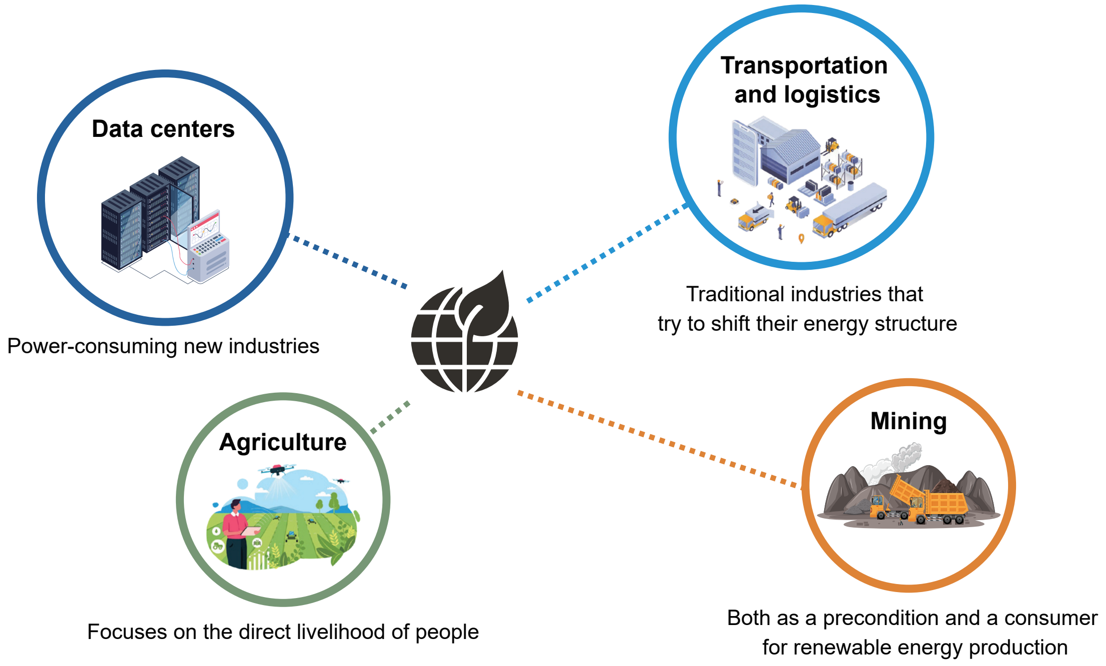
In relation to the three questions raised in Chapter I, supply diversification answers “for whom” by giving end-users, industries, and governments more energy options. It protects values such as affordability, reliability and autonomy. It addresses threats created by fossil-fuel price volatility, import disruption and geopolitical concentration.

2.2

SUPPORTING CRITICAL SECTORS

Renewable energy enterprises also contribute to energy security by connecting clean energy supply with sectors whose operation is essential to the development of economy and human society, while industrial bodies can help develop sector-specific guidance, model contracts, technical standards, and policy recommendations that allow renewable energy solutions to be deployed more quickly and consistently. Such sectors include digital infrastructure, transport and logistics, mineral production, and agri-food systems, etc. This report focuses on these sectors not because they consume large amounts of energy, but because their energy demand represents different circumstances under the process of energy transition. The data centers represent power-consuming new industries, while transportation and logistics signifies traditional industries that try to shift their energy structure. The mining activities act both as a precondition and a consumer for renewable energy production. And energy use in agriculture focuses on the direct livelihood of people. Renewable energy enterprises strengthen energy security by providing these sectors reliable and affordable services rather than manufacturing sets of power generators.

The dramatic rise of AI has become one of the most widely discussed topics in recent years, and forms a reciprocal relationship with the energy sector. On the one hand, surging data centers have already created enormous demand for electricity, and the momentum is forecasted to accelerate in the future. In 2024, data centers consume approximately 415 TWh of electricity, accounting for 1.5% of global electricity consumption, and the consumption is expected to increase by about 60% to 300% in 2030 under different scenarios (IEA 2025). Renewable energy industry therefore becomes part of the physical foundation of the digital economy, with many Big Tech companies setting ambitious targets for renewable energy consumption, both as a major energy source and a means to reduce carbon emissions (IEA 2025). Specific measures of increasing renewable energy consumption include long-term power-purchase agreements (PPA), direct supply, green electricity procurement, storage deployment, and coordination with grid operators. By coordinating with data center consumers to implement these means flexibly, renewable energy enterprises can enhance the sector’s competitiveness by limiting additional reliance on fossil-based generation, reducing carbon-related compliance pressure, and improving long-term price predictability (Simões et al. 2025).



Emissions reduction and clean energy targets of corporate data centre operators

Company	Estimated datacentre capacity(MW)	Net zero emissions target year	Corporate clean, green or renewable electricity target*	Current share	Hourly matching target*
Meta	9780	2030	100% renewable since 2020	100%	
Google	8960	2030	100% renewable since 2017	100%	100% by 2030
Amazon	7660	2040	100% renewable since 2023	100%	
Microsoft	6970	2030	100% renewable by 2025	100%	100% by 2030
Digital Realty	2740	2030		66%	
Equinix	1850		100% renewable by 2030	96%	
Tencent	1760	2030	100% green by 2030	12%	
Alibaba Cloud	1660	2030	100% clean by 2030**	56%***	
Aligned	1290	2040	100% renewable since 2020	100%	
Huawei	1260	2040		>50%	
Apple	1240	2020	100% renewable since 2018	100%	
Vantage	1180	2030		58%	
CyrusOne	1120	2030	100% carbon-free energyby 2030	62%	
NTT Data	1110	2035	100% renewable by 2030**	49%	
QTS Data Centers	1060			65%****	
Baidu	980	2030		5%	
GDS	980	2030	100% renewable by 2030	36%	
Chindata	900	2060	100% renewable by 2040**	7%	
Switch	660	2021	100% renewable since 2016	100%	
Princeton Digital	620	2030	100% green by 2030	14%	

Data source: IEA 2024, p. 76, Table 2.2

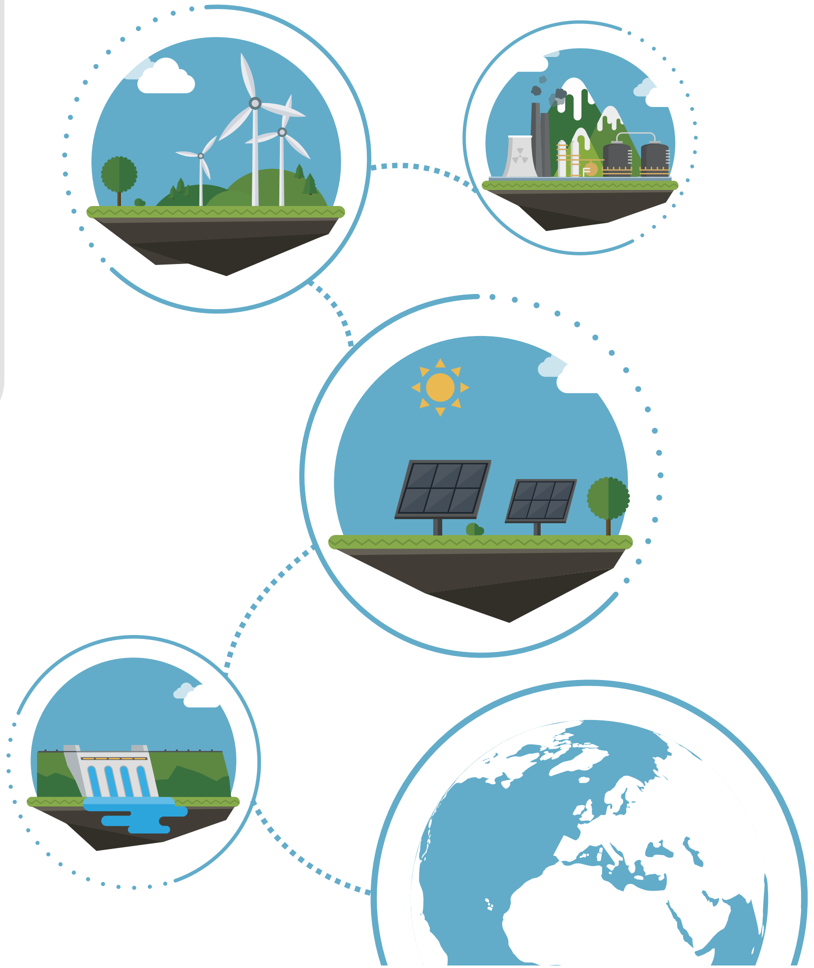
The transport and logistics sector are undergoing a profound transition towards electrification powered by renewable energy. The movement of people, goods and industrial inputs has traditionally depended heavily on fossil fuels, making transport systems exposed to fuel-price volatility, import dependence, and geopolitical disruption. As electric mobility occupies higher share in the market - which is supported by current policy settings, part of this dependence is transferred from liquid fuels to electricity and charging stations (IEA 2024). Bento et al. (2024) quantify four energy policies’ impact on 12 indicators related to energy security, and ultimately identify that among these four policies, transport electrification scores best in 7 indicators, proving the importance of this measure. Renewable energy enterprises contribute to this process by providing key electronic components, supplying low-carbon electricity for charging networks, and providing clean power for electrified public transport systems. On the other hand, the Smart Freight Centre’s Road Freight Electrification Guidance shows how an industry association can reduce coordination barriers between shippers, carriers, and infrastructure providers. It offers recommendations on electrification roadmaps, depot charging, lifecycle emissions accounting and procurement incentives, helping logistics actors align operational decisions with zero-emission freight deployment (Smart Freight Centre 2026).

Mining activities of crucial minerals demonstrate a different position because they are part of the upstream foundation of the energy transition itself. Solar panels, wind turbines, batteries, and grid equipment all require minerals whose extraction and processing depend on large amounts of energy. The IEA emphasizes that mineral supply can either accelerate clean energy deployment or slow it down if investment, processing capacity, and environmental performance fail to keep pace with growing demand (IEA 2024). Renewable energy enterprises therefore contribute to energy security in mining by changing the energy structure of mineral production. In remote mining areas, hybrid renewable systems can reduce reliance on diesel transport and onsite fossil-fuel generation, while lowering the carbon footprint of the materials used in clean-energy technologies.

Goldwind's participation in the Agnew Hybrid Renewable Microgrid in Western Australia provides a useful example: the project uses wind, solar, battery storage, and backup generation to supply Gold Fields' Agnew mine (Goldwind 2019). This project represents the interconnection between minerals and renewable energy: renewable energy enterprises require raw materials to product and innovate, while mining activities increasingly need cleaner power to remain compatible with energy security and transition legitimacy.

Agri-food systems bring renewable energy back to the livelihood dimension of energy security. Farming, irrigation, food processing, and cold-chain logistics all depend on energy, while many rural producers still face weak grids, expensive diesel, and growing climate impact. IRENA and FAO (2021) connect renewable energy in agri-food systems with food security, rural development, and climate goals, especially through applications such as solar irrigation, decentralized power, and renewable-powered processing. SolarPower Europe's guideline (2023) shows how a solar industry association can create shared guidance for projects that combine agricultural production with PV generation. It identifies agrisolar solutions for dual land use, additional revenue schemes for farmers, and greener rural development, while advising solar companies, agricultural actors, investors, landowners, local authorities, and industry associations on implementation. Agriculture therefore shows that energy security is also about protecting people's livelihood: clean power becomes meaningful as it supports food production, rural income, and daily welfare.

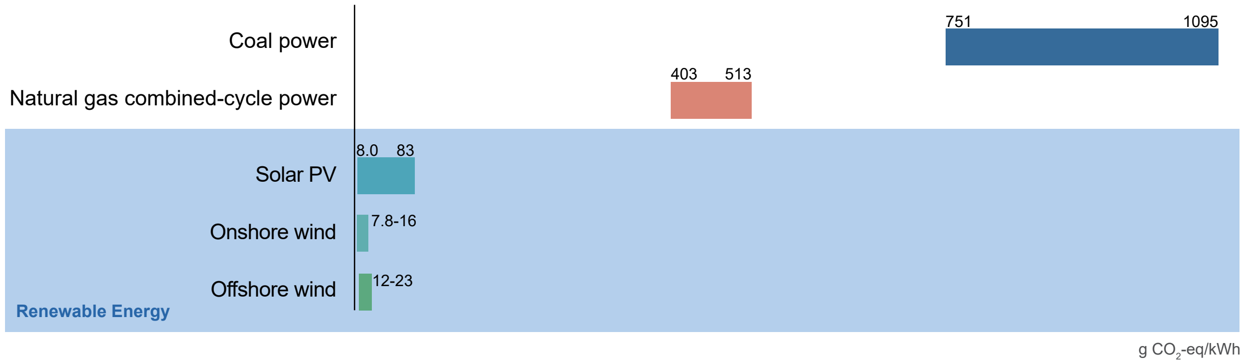
This section extends the 'for whom' question to the specific users in critical sectors, including but not limited to digital services, industrial production, mobility, and agriculture. The stable and resilient development of the mentioned sectors, as well as other sectors benefit from renewable energy stands for the value that needs to be protected itself. Renewable energy addresses threats created by fast-growing electricity demand, fuel-price exposure, weak grid access, and climate-related impact on production systems. From the industrial viewpoint, this contribution depends on its ability to move beyond selling equipment or electricity in isolation and instead organize energy solutions around the operational needs of sectors that society cannot afford to interrupt.



2.3 CLIMATE MITIGATION AND SYSTEM RESILIENCE

Although in some national policies are viewed separately and even contradictory, energy security and climate change are closely bonded and have overlapped interests (Toke & Vezirgiannidou 2013). According to a report of the Energy Institute, global emissions from energy grew by about 1% in 2024 and reached 40.8 GtCO$_2$e, while fossil fuels still accounted for 87% of the global energy mix (Energy Institute 2025). In terms of electricity generation, Ember finds that fossil fuels supplied 59.1% of global electricity in 2024, including 34.4% from coal, 22% from gas and 2.8% from other fossil fuels, while renewable energy generated a record 858 TWh of electricity (Ember 2025). The emission gap between the fossil fuels and renewable energy is large.

▸Carbon emission of different energy source



Data source：UNECE 2022

Therefore, in order to achieve the Paris Agreement climate target, the renewable energy sector becomes increasingly indispensable. A report estimates that global renewable power capacity must reach 11.2 TW by 2030, with an average annual increase of 1,122 GW between 2025 and 2030 compared to the 581.9 GW increase in 2024 (IRENA, COP30 Presidency, & Global Renewables Alliance 2025). Gielen et al. (2019) emphasize that renewable energy and energy efficiency are the core elements of an accelerated global energy transformation, and make a positive prediction that renewable energy can support 63% of primary energy supply by 2050. Scaling up renewable energy is not only an effective way to address climate change, but also a cost-effective one. A recent study models 22,821 solar and wind power stations deployment across 192 countries under Paris-aligned net-zero pathway and proposes an optimized strategy with coordinated deployment of generation, storage, transmission, mineral trade, and supply chains (Wang et al. 2025). This strategy could reduce the average carbon reduction cost from USD 140/tCO$_2$ in the baseline case to USD 33/tCO$_2$ (Wang et al. 2025). Such finding echoes with the coordinated role of the renewable energy industry: on the one hand its products and services contribute directly to the reduction of GHG emissions; on the other hand, industry associations can help translate scattered technological progress into shared standards, policy priorities, and cross-sector collaboration, thereby creating synergy for the holistic transition of the entire energy system.

With all the climate policies and efforts made by policy makers, asset owners, and other stakeholders, higher emissions signify higher transition costs. The mechanism of carbon pricing continues to create capital flow: the World Bank reports that carbon-pricing revenues reached USD 104 billion in 2023, with relevant instruments covering around 24% of global emissions (World Bank 2024). Statistics from the European Union's Emissions Trading System (EU ETS) demonstrate that emissions from power and industry installations fell by 16.5% in 2023 in Europe, while auction revenues reached EUR 43.6 billion (European Commission 2024). Fossil-based energy companies are therefore more likely to face rising pressure from carbon prices, regulatory targets, and customer decarbonization requirements. Their own strategies reflect such pressure: bp developed 8.2 GW of renewable energy capacity to final investment decision and more than 39,000 EV charge points in 2024, while Shell states that it has achieved 60% of its target to halve Scope 1 and 2 operational emissions by 2030 (bp 2024; Shell 2024). Such climate efforts provide renewable energy enterprises with substantial space on reducing the emissions burden of the energy services on which society depends.

At the same time, renewable energy systems are themselves exposed to climate and weather risks, including weather pattern shift, droughts, storms, heatwaves, and other extreme events. The Iberian blackout on 2025 provides an important reminder.

An investigation concluded that the blackout in Spain and Portugal resulted from a series of interconnected factors: voltage fluctuations and oscillations resulted in large scale generation disconnections in Spain, then turned into a series of overvoltage disconnections, and eventually leading to the Iberian system losing synchronism with the Continental Europe Synchronous Area (ICS Investigation Expert Panel 2026).This matters for the role of the renewable energy sector because renewable energy facilities increasingly participate in the same operational dynamics that determine whether electricity supply remains stable under disturbance. In this sense, enhancing climate resilience is therefore one of renewable energy's major contributions to energy security, while also placing higher security requirements on renewable-based energy systems themselves.

However, higher share of renewable energy does not necessarily increase power system vulnerability. A study based on 2,156 bulk-system blackout events and daily weather data from cities across the United States demonstrates that grids with higher wind and solar penetration did not exhibit higher blackout vulnerability (Zhao, Li, & Zhang 2024). The same research also finds that, when weather rarity changes from mild to extreme conditions, the blackout rate increases by 0.33%, with 95.60% of that increase attributed to the direct effect of extreme weather and only 4.40% explained through weather-dependent renewable penetration (Zhao, Li, & Zhang 2024). Such results highlight that vulnerability issues are rather a test to the renewable energy system than a consequence caused by increasing use of renewable energy. It also promotes the adoption of holistic thinking when considering how to maintain energy security through renewable energy.

This is where renewable energy enterprises have a distinctive role. The evidence above suggests that vulnerability under climate stress is primarily a system-wide and weather-driven challenge, rather than an inevitable consequence of higher renewable penetration. Meeting that challenge therefore requires stronger forecasting, operational coordination, and grid-support capability alongside additional clean generation. Renewable energy enterprises are moving beyond equipment supply toward integrated offerings that combine generation with storage, grid services, and digital operation. Zywiolek, Wolniak, and Grebski (2025) show that digitalization and green innovation in the energy sector are adopted to cut operating costs, improve processes, enhance health, safety and environmental performance, and raise production efficiency. Applied to power-system operation, tools such as AI-based forecasting and digital twins can improve dispatch under weather variability and help stabilize the grid when climate impacts intensify. These capabilities allow renewable energy enterprises to reduce system vulnerability and strengthen resilience, which speaks directly to the "for what threats" question in Chapter I. Renewable energy thus contributes to energy security by helping the wider energy system withstand and recover from climate-related disruptions.

2.4

RESPONSIBLE AND JUST SUPPLY CHAIN TRANSFORMATION

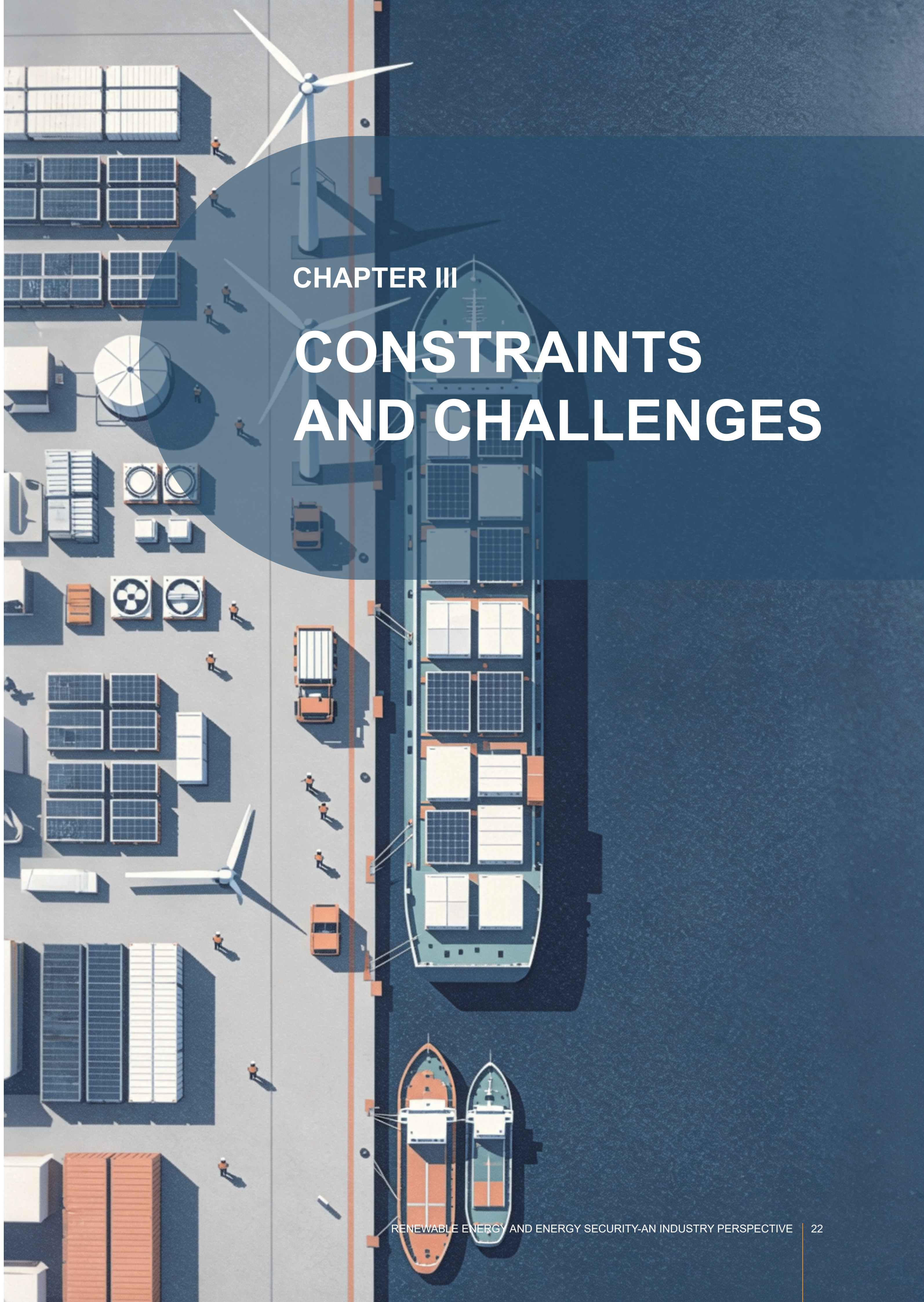
Supply-chain transformation is another way in which renewable energy enterprises contribute to energy security. Renewable energy companies' every decision on research and development, procurement standards, supplier selection, manufacturing locations, and recycling arrangements can affect upstream resource development and downstream market practices. These practices, together with efforts made within renewable enterprises' own operation, have the potential to reduce the overall vulnerability of the whole supply chain while improve its resilience. Possible pathways include improving material efficiency, substitution, recycling, and relocalization (Mertens et al. 2024). These pathways can be reflected in existing enterprise practice.

For example, Vattenfall illustrates how a wind developer can extend supply-chain responsibility into decommissioning: it banned landfilling of blades from its own wind farms in 2021 and aims to reuse, recycle or recover all decommissioned blades by 2030, and in 2024 it added a target for fully circular treatment of permanent magnets in turbines retired from 2030 onward—components that concentrate rare-earth supply (Vattenfall 2021; Vattenfall 2024).

Large enterprises also influence the standards followed by suppliers and downstream project developers. When leading manufacturers require traceability, carbon-footprint disclosure, or recycling capacity from their suppliers, these requirements can gradually shape industry expectations. Industry associations and international bodies can accelerate this process by translating scattered corporate practices into common guidance, certification expectations, and policy recommendations. IRENA (2024) states that expanding solar PV requires compliance with international standards and certification schemes, stronger ESG standards, and more diversified and resilient supply chains. Similarly, the Global Solar Council identifies supply chains, sustainability, and finance as core work areas for the solar industry, showing how industry organizations can connect corporate practice with broader sectoral priorities. This supports the view that the renewable energy industry influences energy security not only through production and deployment, but also through the standards, traceability systems, and sustainability practices that ensure clean-energy products meet global stakeholders' ESG expectations. A supply chain that cannot prove where its materials come from, how its products are made, or how waste will be managed is more vulnerable to trade barriers, reputational damage, and regulatory disruptions.

The communities and stakeholders outside the renewable energy industry can also be affected by the industrial actions, and thus also need to be considered when talk about energy security in this sector. Communities affected by mining, manufacturing, or project construction may not purchase renewable energy facilities, and even do not directly benefit from them. However, under some circumstances they still bear part of the cost of clean-energy deployment through land use change, water stress exertion, and local environmental impacts. In the Salar de Atacama basin in Chile as an example, researchers find that lithium extraction has resulted in serious water stress and impact on hydrological environment, as well as indigenous communities' cultural concern (Jerez, Garcés, & Torres 2021). Yet, renewable energy projects can also contribute to energy security in way aligned with broader communities' interests. A Chinese solar initiative since 2013 has deployed PV projects in high-poverty rural villages through village-level arrays, joint construction arrays and household rooftop systems, allowing local communities and impoverished households to receive income from solar generation. Among 211 pilot counties included in this project, the policy increased county-level rural per-capita disposable income by about 7–8%, with stronger effects in more impoverished regions (Zhang et al. 2020).

The two cases mentioned above show that renewable energy projects can be a double-edged-sword for local communities and vulnerable populations. This is why community engagement and just transition matter for renewable energy enterprises. Taking these issues into consideration requires the renewable energy industry to develop governance tools that prevent social conflict from becoming energy-system vulnerability. Large enterprises can influence this process through procurement standards, supplier audits, community engagement, traceability systems, and end-of-life arrangements, thereby extending their energy-security role beyond the boundary of the industry itself. Returning to the three crucial questions raised in Chapter I, the discussion of supply chain and transition expands renewable energy's security role from securing clean-energy delivery to protecting the welfare of wider stakeholders, especially by serving workers and local communities, safeguarding justice, and social legitimacy, and reducing threats arising from exclusion, conflict and unsustainable resource use.



CHAPTER III

CONSTRAINTS AND CHALLENGES

The previous chapter has discussed how renewable energy enterprises can contribute to energy security through supply diversification, critical-sector support, climate resilience, and responsible transformation. However, various constraints and challenges need to be addressed in order to fully unleash renewable energy industry's potential.

> **Renewable energy industry operates inside a wider system shaped by minerals, grids, markets, infrastructure, regulation, and social acceptance. Its ability to strengthen energy security therefore depends on whether these enabling factors are sufficiently mature and can be engaged with properly.**

Following the logic developed in Chapter II, this chapter analyzes major constraints and challenges confront by the renewable energy industry in detail. As the industry's role in energy security is regarded as a process of-multi-layered economic resilience across technologies, laws and regulations, infrastructure, markets, and stakeholder responsibilities, specific constraints and challenges are more likely to occur precisely where such coordination becomes difficult. This report identifies five main aspects of these constraints: resource deficiency and consequential dependence, grid and system integration, financial and market mechanism, technological threshold, and geopolitical factors. Although such difficulties can undermine the contribution of renewable energy in terms of guaranteeing energy security, overcoming them can promote a healthier and more sustainable development pattern of the industry.

3.1

RESOURCE DEFICIENCY AND DEPENDENCE ON CRUCIAL MATERIALS

In order to harness different types of renewable energy, certain critical materials are indispensable. PV module manufacturing depends on polysilicon, silver and aluminum; wind turbines require large volumes of steel, copper and rare earth elements such as neodymium and dysprosium for permanent magnets; batteries rely heavily on lithium, nickel, cobalt, manganese and graphite; and electrolyzers may need nickel, platinum-group metals or iridium depending on the technology pathway. Therefore, renewable energy reduces exposure to imported fossil fuels, while increases dependence on metals, manufacturing capacity, and processing facilities that are under many conditions geographically concentrated, creating a different form of energy-security risk. An investigation on the relationship between several countries' trade risks and energy

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For renewable energy enterprises, such challenge first appears as a supply-chain and cost problem. Material shortages, price volatility, and processing concentration can increase production costs, delay delivery schedules, and weaken the competitiveness of clean-energy projects. Iridium provides a clear example of how a small material stream becomes a strategic bottleneck. PEM electrolyzers are attractive for green hydrogen production partly because they can respond flexibly to variable renewable electricity. However, commercial PEM systems still rely on iridium, which is characterized by low crustal abundance and limited production volumes. This metal is mainly produced as a byproduct of platinum-group mining, and thus its supply and price are relatively inelastic to demand growth, making PEM electrolyzer deployment increasingly exposed to material availability and price volatility (Hubert, King, & Jaramillo 2022). Therefore, PEM electrolyzer expansion depends not only on hydrogen demand, but also on reducing iridium intensity, improving catalyst recovery, and developing alternative designs. Upstream concentration also creates compliance and procurement risks, as enterprises increasingly need to prove where their materials come from and whether suppliers meet sustainability standards, questioning the reliability, transparency, and bankability of the whole supply chain.

Renewable energy industry can mitigate such vulnerability through improving product design to lessen material consumption. For example, in order to reduce iridium dependence, Lee et al. (2023) propose an ionomer-free porous-transport electrode that enables less iridium use and easier recycling, achieving high PEM water-electrolysis performance with an iridium loading under 0.1 mgIr cm^{-2}, while maintaining high durability. Another measure of reducing material dependence is to optimize end-of-life operations, such practice can be found in the battery production sector.

Brunp has built a full-life-cycle closed loop covering battery production, use, recycling, recycled materials, and remanufacturing. According to CATL, Brunp processed more than 120,000 tons of waste batteries in 2024 and produced 17,100 tons of recycled lithium salts, while its Directional Recycling Technology achieved recovery rates of 99.6% for nickel, cobalt, and manganese and 96.5% for lithium (CATL 2025).

3.2

GRID INTEGRATION AND SYSTEM STABILITY

The ability of power systems to absorb a rising share of variable renewable electricity also forms a part of the challenge, with solar and wind power being more likely to be affected, as their generation patterns vary from traditional fossil-fuel plants. The variability of these two energy sources can be presented by steep net-load ramps occurring when renewable output changes faster than demand. Such phenomena are commonly visible in solar-based systems, as they require enough flexible capacity to cover the high ramps during sunrise and sunset hours, in order to avoid possible increase of balancing costs and reliability risks. Curtailment represents another aspect of the influence on the renewable energy industry. This happens when renewable electricity is overly generated but cannot be absorbed due to the mismatch between generation sites, demand centers, and grid capacity. Furthermore, persistent adverse weather conditions, such as high-pressure systems, low wind speeds, cloud cover, or low solar irradiation in winter, can lead to prolonged low output periods. An investigation studies 39 years of hourly wind and solar weather data in the United States and finds that gaps in wind and solar availability can last for consecutive days and even weeks, requiring increased participation of long-duration storage to reduce overall system costs (Dowling et al. 2020).

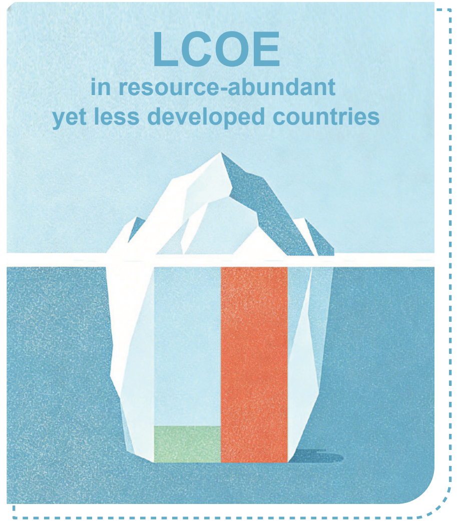
Extreme weather and long-term climate events pose a greater threat to renewable-based energy security as they challenge demand, power generation, and network availability simultaneously. A climate resilience assessment for Chile notes that the continuous decline of precipitation since 1961 together with accelerated rising of temperatures have led to increased summer cooling demand and less water for hydropower generation (IEA 2024). Growing demand in this case is met with shrinking supply capacity, as IEA predicts that Chile's hydropower capacity factor may decline from 14% to 25% under different emission scenarios by the end of the century. Meanwhile, the influence of drought can even expand to the fossil fuel sector, as cooling water for coal and gas plants is also restricted. Such impacts eventually influence broader aspects of Chile's energy structure, for example, reduced hydropower generation during the drought in 2021 resulted in higher demand for coal and diesel, showing how climate impact can push the system back toward higher-emission backup resources (IEA 2024). For the renewable energy industry, this case suggests that climate resilience can push projects to comprehensively consider its design to operate alongside ecological and climate pattern changes, shifting demand peaks, storage needs, and transmission planning.

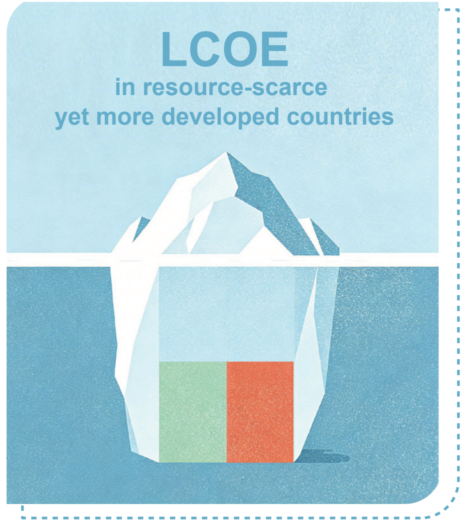
Grid constraints also can be caused by regional development gap as regions with abundant renewable energy resources are often located far from demand centers. Take China as an example, in the country's early rush of renewable energy development, large extent of mismatch existed between its solar and wind sources, which are mostly in northern and northwestern provinces, and its southern and eastern demand centers. Such mismatch contributed to serious curtailment: in 2016, China curtailed 49.7 TWh of wind power and 7.6 TWh of solar PV, with 90% of wind curtailment and 99% of solar PV curtailment on the State Grid occurring in Northwest China (Liu et al. 2018). To address this issue, China invested around USD 75 billion per year in grid infrastructure since 2010 and promoted interconnection between renewable-resource provinces and load centers, helping reduce solar and wind power curtailment from 16% in 2012 to below 3% (IEA 2023). However, the problem is not resolved completely. With distributed PV accounting for 40% of China's total solar capacity by 2024, congestion and connection restrictions appeared in 11 provinces where local demand or distribution-network investment could not absorb distributed PV injection (IEA 2025). This case shows that renewable energy fulfills its contribution to energy security in critical sectors and local development when both transmission and distribution networks are able to deliver it with the quality, timing, and reliability required by end users.

3.3

COST, FINANCE AND MARKET DESIGN

Renewable energy is often described as cost-effective because recent utility-scale solar and onshore wind projects have become cheaper than fossil-fuel alternatives in many markets, while also avoiding exposure to potential fuel-price volatility. In 2024, 91% of newly established utility-scale renewable energy projects generated lower-cost electricity even compared to the cheapest new fossil-fuel alternative, with **a global weighted-average LCOE of USD 0.034/kWh for onshore wind and USD 0.043/kWh for solar PV (IRENA 2025).** However, the price advantage does not signify that financial risks are eliminated for this capital-intensive industry. A large share of renewable energy expenditure is determined by equipment procurement, land acquisition, obtaining governmental permissions, grid connection, and construction, which are usually been made before the project officially starts operation. As a result, interest rates, investment conditions, and policy stability strongly affect project economics.





🟩 resource and output

🟥 financing costs

This is especially important for renewable energy enterprises operating across different markets. A project that appears competitive under low financing costs may become less attractive under high interest rates or uncertain revenue arrangements. Ondraczek, Komendantova, and Patt (2015) conduct a comprehensive analysis on the financing costs of solar PV systems across 143 countries, and state that national differences in the cost of capital are more influential to the LCOE of solar projects than the differences in solar irradiation. IRENA's 2025 cost report provides a more concrete regional comparison: in 2024, its weighted-average cost-of-capital assumptions ranged from 3.8% in Europe to 12% in Africa, and although onshore wind LCOE was similar in the two regions, financing costs formed a much larger part of the African cost structure (IRENA 2025). Thus, the economic competitiveness of renewable energy projects, especially for those in less developed regions, needs to take bankability, offtake certainty, and macro-financial conditions into considerations. Such differences also reflect the mismatch between resource endowment and national development imbalances, elevating the issue of energy security to the level of international business regulations and developmental dynamics.

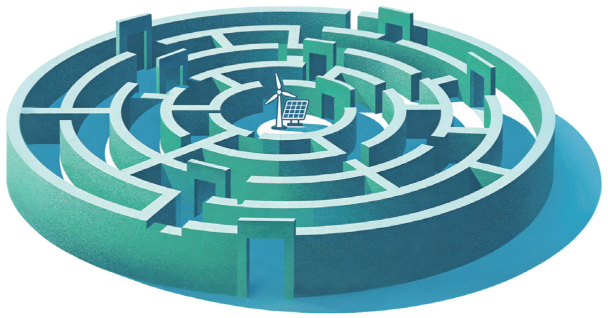
Market design is another source of constraint as the renewable energy industry needs revenue models that reflect not only electricity generation, but also the system services required for higher shares of variable renewable energy. Theoretically, electricity markets can reflect the value of flexibility through time-varying prices, yet wholesale electricity markets may provide insufficient incentives for flexibility because real-world pricing rules can weaken the price signals that should reward resources able to respond across time (Mays 2021). This matters for the renewable energy industry because additional wind and solar capacity can lose system value if markets do not reward the flexibility needed to integrate variable output reliably. Such flexibility can be supported by storage system, demand response, and aggregated distributed energy resources. However, their market participation often depends on rules that were originally designed around large conventional generators. The IEA (2026) notes that demand-response implementation remains largely untapped globally, with only around 100 GW utilized in 2024. It attributes the gap between economic potential and actual use partly to market barriers, regulatory frictions, and behavioral inertia, while also noting that restrictions on small-load aggregation limit participation in some markets. Such lack of a dependable incentive mechanism may undermine commercial interests to invest in the system capabilities needed to turn variable output into reliable energy services, hindering long-term development of the renewable energy industry.

Carbon-related market rules may also affect renewable energy industry through product-level carbon accounting. The lack of a comprehensive and authoritative mutual recognition across different accounting systems can generate uncertainties for carbon footprint calculations of renewable energy equipment and facilities. For example, China's recent product carbon-footprint framework places more emphasis on measured domestic data, geographical production conditions, national carbon-footprint factors, and the possible use of green electricity certificates or power-purchase contracts where they meet relevant rules (MEE et al. 2025). The EU battery methodology, however, is more cautious about contractual electricity instruments outside the region, due to worries that environmental attributes may not be uniquely and traceably claimed in some jurisdictions (European Commission 2024). For Chinese renewable energy enterprises, this creates a risk that low-carbon electricity actually used in production may not be fully reflected in EU-facing carbon-footprint calculations. Such divergence means that Chinese renewable energy products may face higher reported carbon values if EU-side assessments rely on outdated secondary datasets or do not accept China-specific electricity factors, verified green-power procurement, and factory-level data. The resulting methodological non-recognition can operate as a potential green trade barrier, increasing compliance costs and weakening the competitiveness of products needed for renewable energy deployment.

3.4

TECHNOLOGICAL THRESHOLD

Technological thresholds are also obstacles for the development of the industry, they appear in mature forms of renewable energy use, appliances towards end-use sectors, as well as emerging forms of energy exploitation. Solar PV and wind are already mature, yet further efficiency gains are becoming harder to obtain through simple scale expansion. In solar PV, crystalline silicon cells are approaching practical efficiency limits, making perovskite/silicon tandem cells a promising route to higher conversion efficiency. Although laboratory devices of this pathway have exceeded 33% efficiency, surpassing single–junction cell technology's theoretical limit, its commercial deployment still confronts issues like solving stability, large-area manufacturing, encapsulation, degradation testing, and field-performance uncertainty (Aydin et al. 2024). Meanwhile, floating offshore wind turbines need to solve reliability of the floating foundation and mooring system. Unlike fixed-bottom turbines, the whole structure moves under wind, wave, and current loads, so the mooring system must keep the turbine within a safe operating envelope while limiting fatigue damage over decades of operation. Additionally, as the turbine platform moves continuously, the cable must transmit electricity while tolerating repeated bending, tension, and seabed interaction, making dynamic power cabling a major hindrance of commercialization of floating offshore wind turbines (Robertson et al. 2025).



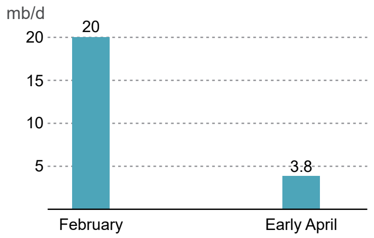
Heavy-duty electric trucks demonstrate an example of technical restriction towards renewable energy transition. The constraint lies in that en-route charging for medium-and heavy-duty vehicles may require megawatt-level fast charging to avoid disrupting operations, while fleets charging multiple trucks at depots may need several megawatts of power and costly grid upgrades (Powell et al. 2024). Therefore, distribution-network capacity, site-specific charging design, and customized battery size are required if a full replacement for diesel logistics is to be achieved (Powell et al. 2024). More emerging renewable energy forms face an even larger gap between resource potential and deployable infrastructure, and ocean energy provides a case in this aspect. It is attractive because marine resources can be more predictable than solar or wind in some locations. Yet in order to harness this type of energy stably, devices must survive corrosion, biofouling, storms, seabed constraints, and difficult maintenance conditions, while developers still need grid connections, specialized vessels, consenting procedures, and supply chains that are not yet available at conventional power-sector scale.

Furthermore, technical barriers also exist in quality control of the renewable energy industry. Taking battery production as an example, storage systems and electric trucks depend on thousands of cells working safely as one system, so a small defect at cell level can become a pack-level reliability or safety problem. Attia, Moch, and Herring (2025) note that batteries are difficult to produce at gigawatt-hour scale because of their sensitivity to minor manufacturing variation, as a 38 GWh/year factory may produce about six million cylindrical cells per day while still needing micron-level tolerances and strict control of particle contamination. Many critical defects are small, rare and hard to detect at production speed. Metallic particles, uneven electrode coating, welding defects, or separator damage may not immediately cause failure, but can later trigger internal short circuits, accelerated degradation, or thermal runaway. Quality control therefore becomes a bottleneck because manufacturers must combine high throughput with precise inspection, non-destructive testing, and reliable defect prediction before batteries can safely support large-scale storage and electric freight systems.

3.5 GEOPOLITICAL AND TRADE POLICY

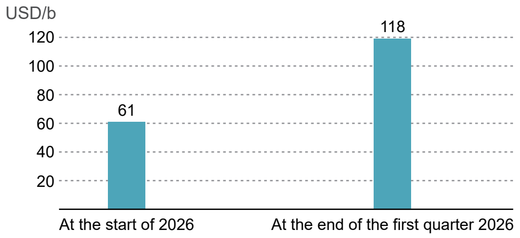
Being connected with manufacturing capacity, technological leadership, employment, climate attitude, and energy independence, the renewable energy industry is at the center of trade policy and geopolitical relationship debates. Recent conflicts around the Strait of Hormuz have generated substantial influences on fossil fuel supply and price.

Average shipments of fossil fuel product through the Hormuz Strait



Data source: IEA 2026

Brent Crude Oil price



Data source: EIA 2026

Geopolitical tensions in such instances may create opportunities for the renewable energy industry.The impact on fossil fuel section led to the increased contribution of renewable energy source, as in the first month after the Strait closure, solar and wind generation outside China witnessed a 14% and 8% increase separately (Myllyvirta 2026). Meanwhile, 68 gigawatts of Chinese solar technology were exported in March, breaking the previous record by 50%, with the most significant demand growth coming from Asian and African countries influenced severely by the energy crisis (Yang 2026).

On the other hand, geopolitical tensions can also generate negative impacts on the development of renewable energy industry. Once renewable energy facilities and products are treated as strategic assets, trade policy no longer evaluates them only through cost, emissions performance, or consumer benefit. Governments begin to ask who controls production capacity, whether domestic firms can survive import competition, and whether dependence on foreign suppliers creates security risks. Under such circumstances, renewable energy products are likely to become targets of state control and defensive trade regulations. In 2024, the United States raised Section 301 tariffs on Chinese electric vehicles to 100%, effectively making direct exports to the U.S. market commercially unrealistic for many Chinese producers (USTR 2024). The European Union adopted a less absolute but still restrictive approach, imposing additional countervailing duties on Chinese-made battery electric vehicles. However, with European’s decisive actions towards electric vehicles, these duties are unlikely to stop Chinese brands’ expansion in Europe, as affordable Chinese cars can accelerate the shift of production into Europe, with BYD already preparing factories in Hungary and Turkey (Fechner & Luman 2024). The complexities of geopolitical tension therefore force the renewable energy industry to decide their strategy based on regional nuances: whether to absorb tariffs, raise prices, localize production, or redirect exports to other markets.

Globalized supply chains have helped reduce renewable energy costs but also have created political sensitivity. Countries may worry that dependence on imported equipment weakens their own energy security. In response, governments may promote domestic manufacturing, diversify suppliers, or impose trade restrictions. However, the boundary between reasonable support for local renewable energy industry and fragmented protectionism is often blurred. Fang (2025) describes recent green industrial policies as multi-purpose measures in which climate, trade, supply resilience, and national security interests are increasingly intertwined, and argues that the blending of policy objectives will possibly foster zero-sum thinking and ally mindset across a small group of “like-minded” countries. For the renewable energy industry, this creates a security paradox: measures introduced in the name of resilience may disrupt global clean-energy value chains, reduce market efficiency, raise deployment costs, and divide supply chains into competing blocs. The risk is especially serious for countries and firms that cannot match the fiscal capacity of major economies, as they may be pushed to the margins of clean-energy production and trade.

CHAPTER IV

POLICY RECOMMENDATIONS

The preceding chapters have discussed the definition, the role and contribution, as well as the constraints of renewable energy security from the industrial point of view. This report highlights that renewable energy can only serve energy security effectively if policies create the enabling conditions under which clean energy can be converted into reliable services, traded across open and trusted markets, and governed in a socially legitimate way. The central policy task is therefore to support the renewable energy industry in exercising its role across technologies, infrastructure, markets, and stakeholder responsibilities and eventually reduce the vulnerability while strengthening the resilience of the energy system.

4.1 BUILD GRID-CENTERED RENEWABLE DEPLOYMENT

▶ Shift from capacity targets to deliverability targets.

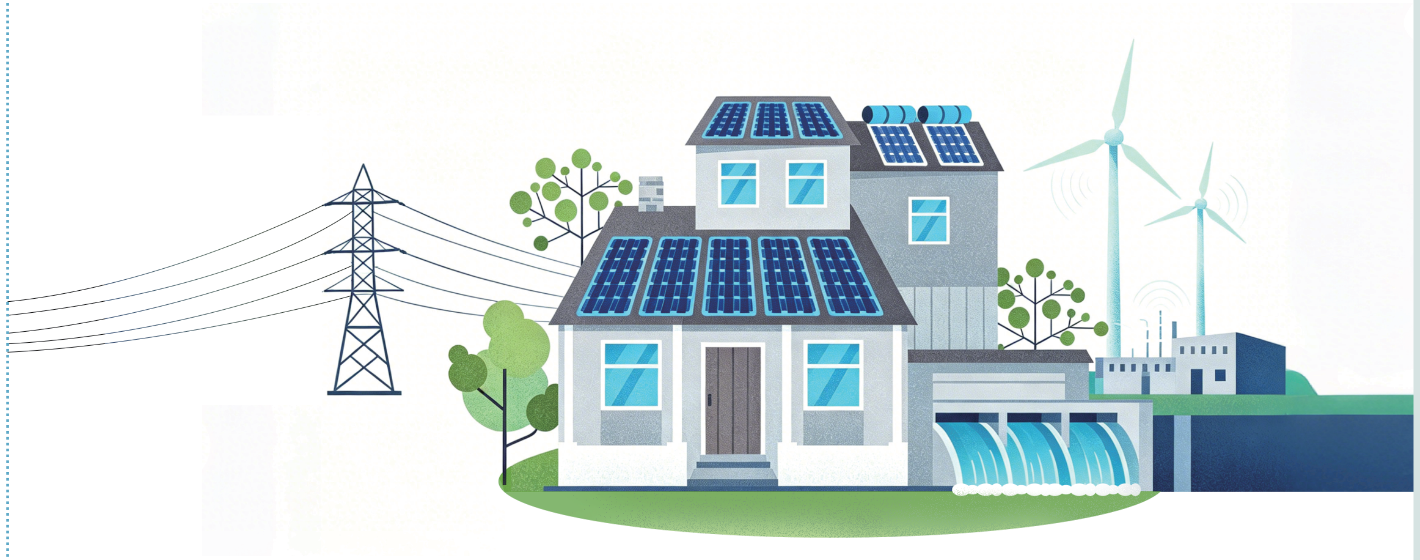
Renewable energy policy should change its development model from mere capacity expansion to establishing comprehensive capability to reach end-users with adequate timing, reliability, and traceability.

▶ Improve the transparency and timing of grid-readiness assessment.

Grid access is already part of renewable project development in many jurisdictions, yet developers may still face uncertainty over connection timelines, congestion, and curtailment. Such issues can be addressed by disclosing available hosting capacity, upgrading schedules, and expected connection constraints in advance.

▶ Plan flexibility together with renewable generation.

Storage, demand response, interconnection, digital dispatch, and flexible operation should be considered from the beginning of renewable deployment. These resources help manage variability, net-load ramps, and prolonged low-output periods, allowing renewable electricity to become a more reliable energy service.



4.2 MAKE FLEXIBILITY COMMERCIALLY INVESTABLE

▶ Create stable revenue streams for flexibility services.

Electricity markets should design a mechanism that reflect and incentivize the ability to shift, balance, and stabilize supply. Storage, demand response, and other flexible resources need predictable revenues from ancillary services, capacity adequacy, congestion relief, and long-duration balancing, otherwise they may fail to attract sufficient investment.

▶ Remove participation barriers for flexible resources.

Market rules should be updated so that storage, demand response and aggregated distributed resources can participate in energy service markets where they meet performance requirements. Existing barriers often arise from rules designed around conventional generators, minimum size thresholds, aggregation limits, or incomplete price signals.

▶ Link renewable deployment incentives with system-integration value.

Support schemes should encourage projects that reduce system stress, not only those that offer the lowest generation cost. Auctions or contracts can give additional value to renewable projects that include storage, firm supply commitments, demand-side coordination, or grid-supporting capabilities.

4.3 ADDRESS CRITICAL MATERIAL RELIANCE

▶ Promote higher material efficiency, substitution, and recycling.

Policy should promote industrial practices to reduce the intensity of vulnerable materials, develop alternative designs, and establish end-of-life recovery systems. This can be done through R&D support, product standards, and procurement regulations that reward lower material dependence and higher recoverability.

▶ Develop globally-distributed supply chains.

Critical-material security should rely on geographically diversified mining, processing, manufacturing, and recycling capacity. Governments can support this by encouraging long-term partnerships between renewable energy enterprises and mineral-producing countries, financing cross-border processing and recycling projects, and improving information sharing on supply risks.

▶ Turn recycling commitments into usable secondary supply.

Recycling should not remain only a corporate sustainability pledge. Policy makers should support traceability, collection channels, and quality standards that allow recovered lithium, nickel, cobalt, rare earths, silver, or module materials to re-enter manufacturing.

4.4 BALANCE RESILIENCE WITH OPEN AND FAIR SUPPLY CHAINS

▶ Ensure supply chains remain affordable while enhancing traceability.

Governments should implement strategic procurement policies that balance supply-chain security with affordability and rapid renewable deployment. Trade and industrial policies should avoid unnecessary restrictions and instead rely on due-diligence frameworks, transparency measures, and internationally recognized certification and standards systems to support open and fair global supply chain. This is particularly important for countries seeking to accelerate renewable deployment in order to reduce dependence on imported fuels and improve energy security.

▶ Promote harmonized and effective sustainability standards.

Carbon-related actions have the potential to improve climate integrity, and improve sustainability outcomes when they are designed to be transparent, practical, and internationally aligned. Governments should support clear methodologies, mutual recognition of credible certification systems, verified factory-level data, qualified renewable energy procurement, and transparent third-party verification processes. Well-aligned sustainability frameworks can help raise environmental standards while maintaining efficient trade flows, reducing administrative complexity, and supporting broad participation across global supply chains.

▶ Provide industrial support that is targeted and efficient.

Public support for local renewable energy industries should address clear market failures, such as early-stage innovation, grid integration, workforce training or supply-chain risk.

4.5 STRENGTHEN SOCIAL LICENSE AND COMMUNITY BENEFITS

▶ Make community engagement an early project requirement.

Public support for local renewable energy industries should address clear market failures, such as early-stage innovation, grid integration, workforce training, or supply-chain risk. It should avoid open-ended subsidies or rules that mainly shield domestic firms from competition without improving climate performance or energy security.

▶ Strengthen safeguards for land, water and labor.

Social license depends on whether renewable-energy supply chains avoid shifting environmental and social costs onto vulnerable groups. Project governance should include enforceable standards on water use, land acquisition, labor protection, biodiversity, and grievance mechanisms, especially in mining regions and large-scale renewable project sites.

▶ Use public finance to reward responsible practice.

Public banks, export-credit agencies, and green funds can require stronger community consultation, transparent impact assessment, and benefit-sharing plans as financing conditions. This would make responsible project governance part of financial bankability, not just a voluntary CSR commitment.

4.6 STRENGTHEN INDUSTRY COORDINATION AND REPRESENTATION

▶ Use industry platforms to identify deployment bottlenecks.

Policy makers should work more closely with renewable energy associations and global councils to identify practical barriers. Organizations such as the Global Solar Council can help turn these scattered industry experiences into more visible policy signals, especially where deployment problems are difficult for single firms to communicate alone.

▶ Promote common standards and policy alignment.

Industry bodies can support renewable energy security by helping align technical, environmental, and social expectations across markets. This includes work on traceability, ESG disclosure, recycling, storage integration, workforce training, and responsible supply-chain practices. Such coordination can reduce uncertainty for project developers and investors, while improving the credibility of renewable technologies in international trade and public procurement.

Bibliography

Ang, B, Choong, W, & Ng, T 2015, 'Energy security: Definitions, dimensions and indexes', Renewable and Sustainable Energy Reviews, vol. 42, pp. 1077-1093.

Asia Pacific Energy Research Centre (APERC) 2007, 'A Quest for Energy Security in the 21st Century', APERC, Tokyo.

Aslanturk, O, & Kıprızlı, G 2020, 'The Role of Renewable Energy In Ensuring Energy Security Of Supply And Reducing Energy-Related Import', International Journal of Energy Economics and Policy, vol. 10, no. 2, pp. 354-359.

Attanayake, K, Wickramage, I, Samarasinghe, U, Ranmini, Y, Ehalapitiya, S, Jayathilaka, R, & Yapa, S 2024, 'Renewable energy as a solution to climate change: Insights from a comprehensive study across nations', PLOS ONE, vol. 19, no. 6, pp. e0299807.

Attia, PM, Moch, E, & Herring, PK 2025, 'Challenges and opportunities for high-quality battery production at scale', Nature Communications, vol. 16, no. 1, pp. 611.

Aydin, E, Allen, TG, De Bastiani, M, Razzaq, A, Xu, L, Ugur, E, Liu, J, & De Wolf, S 2024, 'Pathways toward commercial perovskite/silicon tandem photovoltaics', Science, vol. 383, no. 6679.

Batool, K, Zhao, ZY, Irfan, M, & Żywiołek, J 2023, 'Assessing the role of sustainable strategies in alleviating energy poverty: an environmental sustainability paradigm', Environmental Science and Pollution Research, vol. 30, no. 25, pp. 67109-67130.

Bento, N, Grubler, A, Boza-Kiss, B, De Stercke, S, Krey, V, McCollum, DL, Zimm, C, & Alves, T 2024, 'Leverage demand-side policies for energy security', Science, vol. 383, no. 6686, pp. 946-949.

bp p.l.c. 2024, 'Annual Report and Form 20-F 2024', bp p.l.c., London.

CATL 2025, 'Brunp Recycling Leads the Formulation of Battery Recycling Standards', Contemporary Amperex Technology Co., Limited, viewed 14 May 2026, https://www.catl.com/en/news/6595.html

Cheng, J, Tong, D, Zhao, H, Xu, R, Qin, Y, Zhang, Q, Bhuwalka, K, Caldeira, K, & Davis, SJ 2025, 'Trade risks to energy security in net-zero emissions energy scenarios', Nature Climate Change, vol. 15, no. 5, pp. 505-513.

Cherp, A, & Jewell, J 2014, 'The concept of energy security: Beyond the four As', Energy Policy, vol. 75, pp. 415-421.

Dowling, JA, Rinaldi, KZ, Ruggles, TH, Davis, SJ, Yuan, M, Tong, F, Lewis, NS, & Caldeira, K 2020, 'Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems', Joule, vol. 4, no. 9, pp. 1907-1928.

EIA 2026, 'Crude oil and petroleum product prices increased sharply in the first quarter of 2026', U.S. Energy Information Administration, viewed 12 May 2026, https://www.eia.gov/todayinenergy/detail.php?id=67424

Ember 2025, 'Global Electricity Review 2025', Ember, London.

Energy Institute 2025, 'Statistical Review of World Energy 2025', Energy Institute, London.

European Commission 2024, Report from the Commission to the European Parliament and the Council on the functioning of the European carbon market in 2023, European Commissions, Brussels.

Fang, MM 2025, 'Multi-Purpose Green Industrial Policy and the WTO: An Unavoidable Clash?', World Trade Review, vol. 24, no. 2, pp. 153-171.

Farghali, M, Osman, AI, Chen, Z, Abdelhaleem, A, Ihara, I, Mohamed, IMA, Yap, PS, & Rooney, DW 2023, 'Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: a review', Environmental Chemistry Letters, vol. 21, no. 3, pp. 1381-1418.

Fechner, I, & Luman, R 2024, 'Chinese EV tariffs push production in Europe; Western brands set to feel the impact too', ING Think, viewed 7 May 2026, https://think.ing.com/articles/eus-final-decision-on-tariffs-for-evs-from-china

Ge, MP, Friedrich, J, & Vigna, L 2026, 'Where Do Emissions Come From? These Charts Explain Greenhouse Gas Emissions by Sector', World Resources Institute, viewed 5 May 2026, https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

Gielen, D, Boshell, F, Saygin, D, Bazilian, MD, Wagner, N, & Gorini, R 2019, 'The role of renewable energy in the global energy transformation', Energy Strategy Reviews, vol. 24, pp. 38-50.

Girgibo, N, Hiltunen, E, Lü, X, Mäkiranta, A, & Tuomi, V 2024, 'Risks of climate change effects on renewable energy resources and the effects of their utilisation on the environment', Energy Reports, vol. 11, pp. 1517-1534.

Gitelman, L, Magaril, E, & Kozhevnikov, M 2023, 'Energy Security: New Threats and Solutions', Energies, vol. 16, no. 6, pp. 2869.

Goldwind 2019, 'Goldwind Australia – Goldwind to deliver the wind farm project at Agnew Mine, the first Australian mine to use wind generation as part of a large hybrid microgrid', Goldwind, viewed 4 May 2026, https://www.goldwind.com/en/news/focus-934762623940056064/

Hubert, MA, King, LA, & Jaramillo, TF 2022, 'Evaluating the Case for Reduced Precious Metal Catalysts in Proton Exchange Membrane Electrolyzers', ACS Energy Letters, vol. 7, no. 1, pp. 17-23.

ICS Investigation Expert Panel 2026, Grid Incident in Spain and Portugal on 28 April 2025: Final Report, European Network of Transmission System Operators for Electricity, Berlin.

International Energy Agency 2026, 'Electricity 2026', IEA, Paris.

International Energy Agency 2024, 'Empowering Urban Energy Transitions: Smart cities and smart grids', IEA, Paris.

International Energy Agency 2024, 'Energy and AI', World Energy Outlook Special Report, IEA, Paris.

International Energy Agency 2025, 'Integrating Distributed Energy Resources in China', IEA, Paris.

International Energy Agency 2026, 'Oil Market Report', IEA, Paris.

International Energy Agency 2025, 'Recycling of Critical Minerals', IEA, Paris.

International Energy Agency 2023, 'Renewable Energy Market Update — June 2023', IEA, Paris.

International Renewable Energy Agency 2024, 'Renewable Power Generation Costs in 2024', IRENA, Abu Dhabi.

International Renewable Energy Agency 2024, 'Solar PV Supply Chains: Technical and ESG standards for market integration', IRENA, Abu Dhabi.

International Renewable Energy Agency 2025, 'Delivering on the UAE Consensus: Tracking progress toward tripling renewable power and doubling the global rate of energy efficiency improvements by 2030', IRENA, Abu Dhabi.

International Renewable Energy Agency & Food and Agriculture Organization of the United Nations 2021, Renewable Energy for Agri-food Systems: Towards the Sustainable Development Goals and the Paris Agreement, IRENA and FAO, Abu Dhabi and Rome.

International Energy Agency 2024, 'National Climate Resilience Assessment for Chile', IEA, Paris, viewed 6 May 2026, https://www.iea.org/reports/national-climate-resilience-assessment-for-chile

Jerez, B, Garcés, I, & Torres, R 2021, 'Lithium extractivism and water injustices in the Salar de Atacama, Chile: The colonial shadow of green electromobility', Political Geography, vol. 87, pp. 102382.

Lee, JK, Anderson, G, Tricker, AW, Babbe, F, Madan, A, Cullen, DA, Arregui-Mena, JD, Danilovic, N, Mukundan, R, Weber, AZ, & Peng, X 2023, 'Ionomer-free and recyclable porous-transport electrode for high-performing proton-exchange-membrane water electrolysis', Nature Communications, vol. 14, no. 1, pp. 4592.

Lenton, TM, Pichler, PP, & Weisz, H 2016, 'Revolutions in energy input and material cycling in Earth history and human history', Earth System Dynamics, vol. 7, no. 2, pp. 353-370.

Liu, S, Bie, Z, Lin, J, & Wang, X 2018, 'Curtailment of renewable energy in Northwest China and market-based solutions', Energy Policy, vol. 123, pp. 494-502.

Mays, J 2021, 'Missing incentives for flexibility in wholesale electricity markets', Energy Policy, vol. 149, article 112010, viewed 4 May 2026, https://www.sciencedirect.com/science/article/abs/pii/S0301421520307217

Mertens, J, Dewulf, J, Breyer, C, Belmans, R, Gendron, C, Geoffron, P, Goossens, L, Fischer, C, Du Fornel, E, Hayhoe, K, Hirose, K, Le Cadre-Loret, E, Lester, R, Maigné, F, Maitournam, H, de Miranda, PEV, Verwee, P, Sala, O, Webber, M, & Debackere, K 2024, 'From emissions to resources: mitigating the critical raw material supply chain vulnerability of renewable energy technologies', Mineral Economics, vol. 37, no. 3, pp. 669-676.

Ministry of Ecology and Environment of the People's Republic of China 2025, Progress Report on the Construction of the Product Carbon Footprint Management System (2025), Ministry of Ecology and Environment of the People's Republic of China, Beijing.

Myllyvirta, L 2026, 'Global fossil power generation fell after the Hormuz closure due to solar and wind growth', Centre for Research on Energy and Clean Air, viewed 8 June 2026, https://energyandcleanair.org/fossil-power-fell-in-march-after-hormuz-blockade/

Office of the United States Trade Representative 2024, 'Notice of Modification: China's Acts, Policies and Practices Related to Technology Transfer, Intellectual Property and Innovation', Federal Register notice, 12 September 2024, Washington, DC.

Ondraczek, J, Komendantova, N, & Patt, A 2015, 'WACC the dog: The effect of financing costs on the levelized cost of solar PV power', Renewable Energy, vol. 75, pp. 888-898.

Owusu, PA, & Asumadu-Sarkodie, S 2016, 'A review of renewable energy sources, sustainability issues and climate change mitigation', Cogent Engineering, vol. 3, no. 1.

Powell, B, Johnson, C, Yip, A, & Snelling, A 2024, 'Electric Medium-and Heavy-Duty Vehicle Charging Infrastructure Attributes and Development', NREL Technical Report.

Robertson, A, Musial, W, Shields, M, Aubault, A, Ikari, M, & Kitzing, L 2025, 'Considerations for the global commercialization of floating offshore wind energy', Nature Reviews Clean Technology, vol. 1, no. 10, pp. 734-749.

Shell plc 2024, 'Strategic Report' (within Annual Report and Accounts and Form 20-F 2024), Shell plc, London.

Sim, LC, & Griffiths, S 2024, 'Renewable energy supply chains between China and the Gulf states: Resilient or vulnerable?', Energy Strategy Reviews, vol. 56, no. 101605.

Simões, F, Henriques, C, Figueiredo, NC, & Silva, PP 2025, 'Efficient power purchase agreement structures for meeting corporate electricity needs with solar energy', Energy, vol. 322, no. 135651.

Smart Freight Centre 2026, ‘Road Freight Electrification Guidance (RFEG)’, Smart Freight Centre, viewed 18 May 2026, https://smartfreightcentre.org/en/projects/completed-project-publications/road-freight-electrification-guidance

SolarPower Europe 2023, Agrisolar Best Practice Guidelines, Version 2.0, SolarPower Europe, Brussels.

Toke, D, & Vezirgiannidou, SE 2013, 'The relationship between climate change and energy security: key issues and conclusions', Environmental Politics, vol. 22, no. 4, pp. 537-552.

United Nations Economic Commission for Europe (UNECE) 2022, Life Cycle Assessment of Electricity Generation Options, UNECE, Geneva.

Vagin, SG, Vasyakin, B, Zakharov, MY, & Shaker, IE 2022, 'Corporate Social Responsibility of Energy Companies: International Experience and Polycriterial Evaluation of Technological Innovations’ Effectiveness', Frontiers in Energy Research, vol. 10, no. 945109.

Vattenfall 2021, 'Vattenfall commits to landfill ban and to recycle all wind turbine blades by 2030', Vattenfall, viewed 6 May 2026, https://group.vattenfall.com/press-and-media/pressreleases/2021/vattenfall-commits-to-landfill-ban-and-to-recycle-all-wind-turbine-blades-by-2030/

Vattenfall 2024, 'Vattenfall sets circular economy target for permanent magnets', Vattenfall, viewed 6 May 2026, https://group.vattenfall.com/press-and-media/newsroom/2024/vattenfall-sets-circular-economy-target-for-permanent-magnets/

Wang, Y, Wang, R, Tanaka, K, Ciais, P, Penuelas, J, Balkanski, Y, Sardans, J, Hauglustaine, D, Cao, J, Chen, J, Wang, L, Tang, X, & Zhang, R 2025, 'Global spatiotemporal optimization of photovoltaic and wind power to achieve the Paris Agreement targets', Nature Communications, vol. 16, no. 1, pp. 2127.

World Bank 2024, 'State and Trends of Carbon Pricing 2024: Executive Summary', World Bank, Washington, DC.

Yahyazadeh, A 2023, 'Review of renewable energy challenges and opportunities in supply chain', International Journal of Engineering and Technology Sciences, vol. 2022, pp. 1-25.

Yang, S 2026, 'The Iran war has the world buying more clean energy. China stands to benefit the most', CNN Business, 26 April, viewed 8 June 2026, https://edition.cnn.com/2026/04/26/energy/china-clean-energy-exports-intl-hnk

Zhang, H, Wu, K, Qiu, Y, Chan, G, Wang, S, Zhou, D, & Ren, X 2020, 'Solar photovoltaic interventions have reduced rural poverty in China', Nature Communications, vol. 11, no. 1, pp. 1969.

Zhao, J, Li, F, & Zhang, Q 2024, 'Impacts of renewable energy resources on the weather vulnerability of power systems', Nature Energy, vol. 9, no. 11, pp. 1407-1414.

Żywiołek, J, Wolniak, R, & Grebski, WW 2025, 'From traditional to digital: The paradigm shift in the energy sector through green innovation', Energy Reports, vol. 14, pp. 1-16.