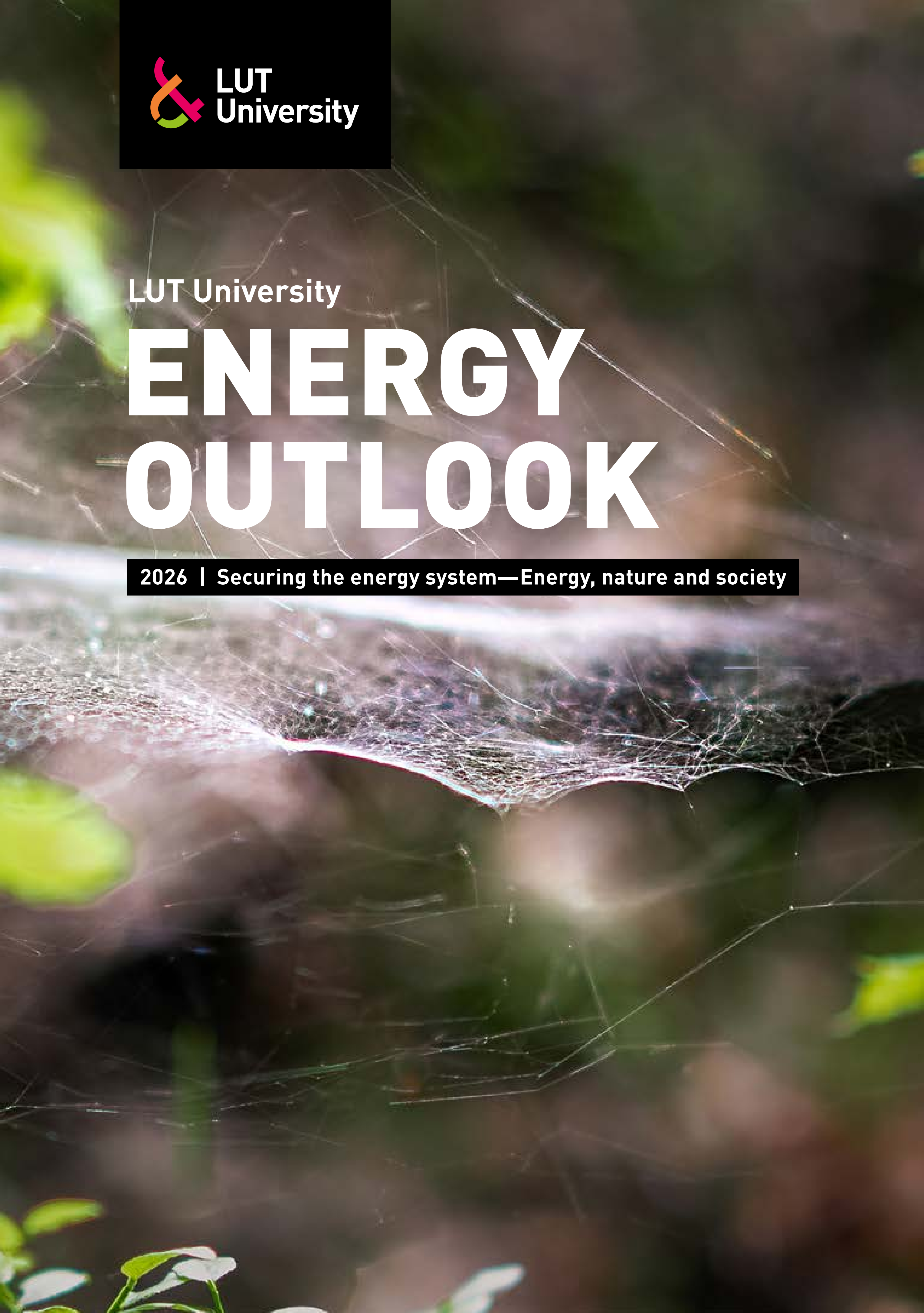

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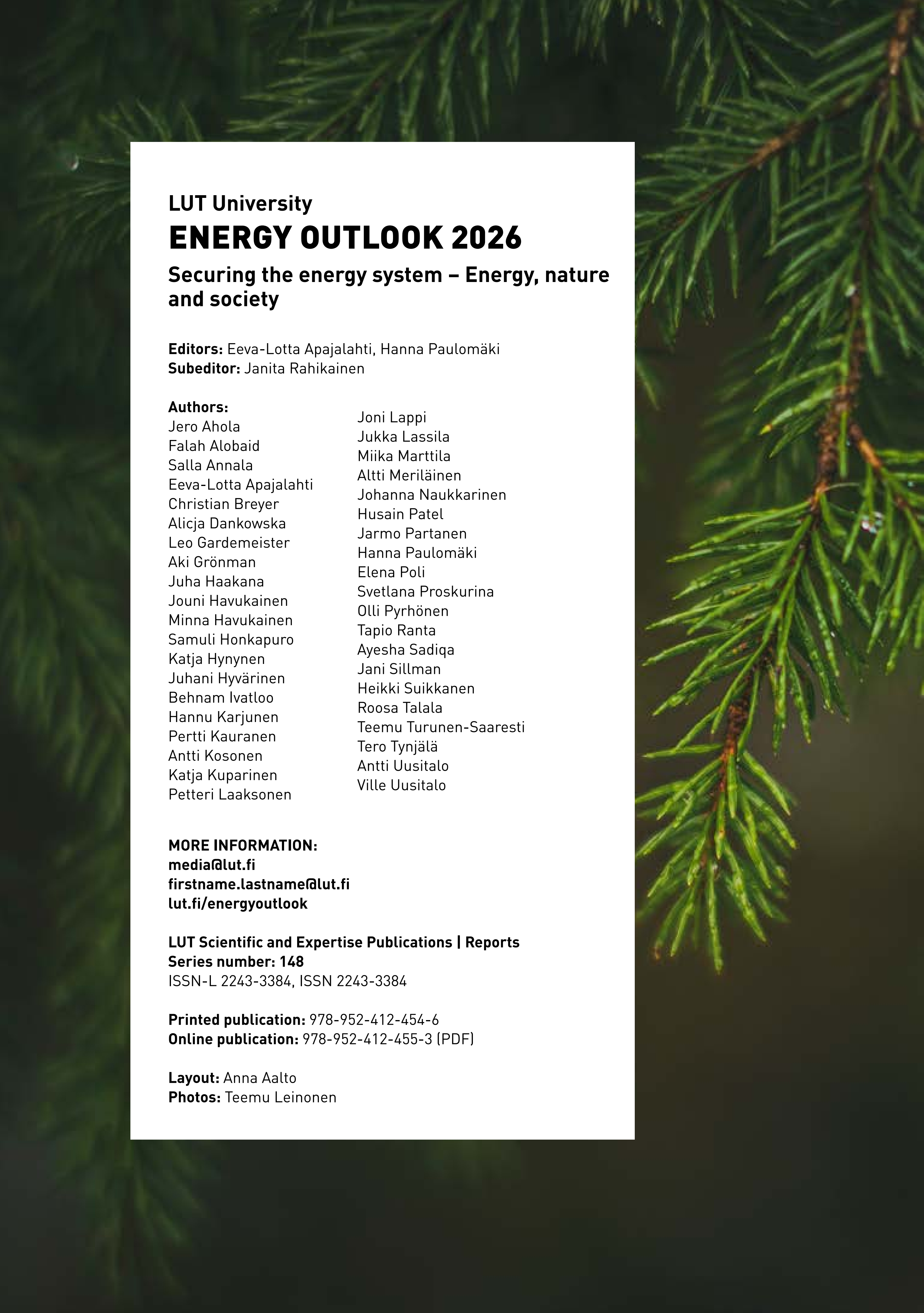
ENERGY OUTLOOK

2026 | Securing the energy system—Energy, nature and society



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ENERGY OUTLOOK 2026

Securing the energy system – Energy, nature and society

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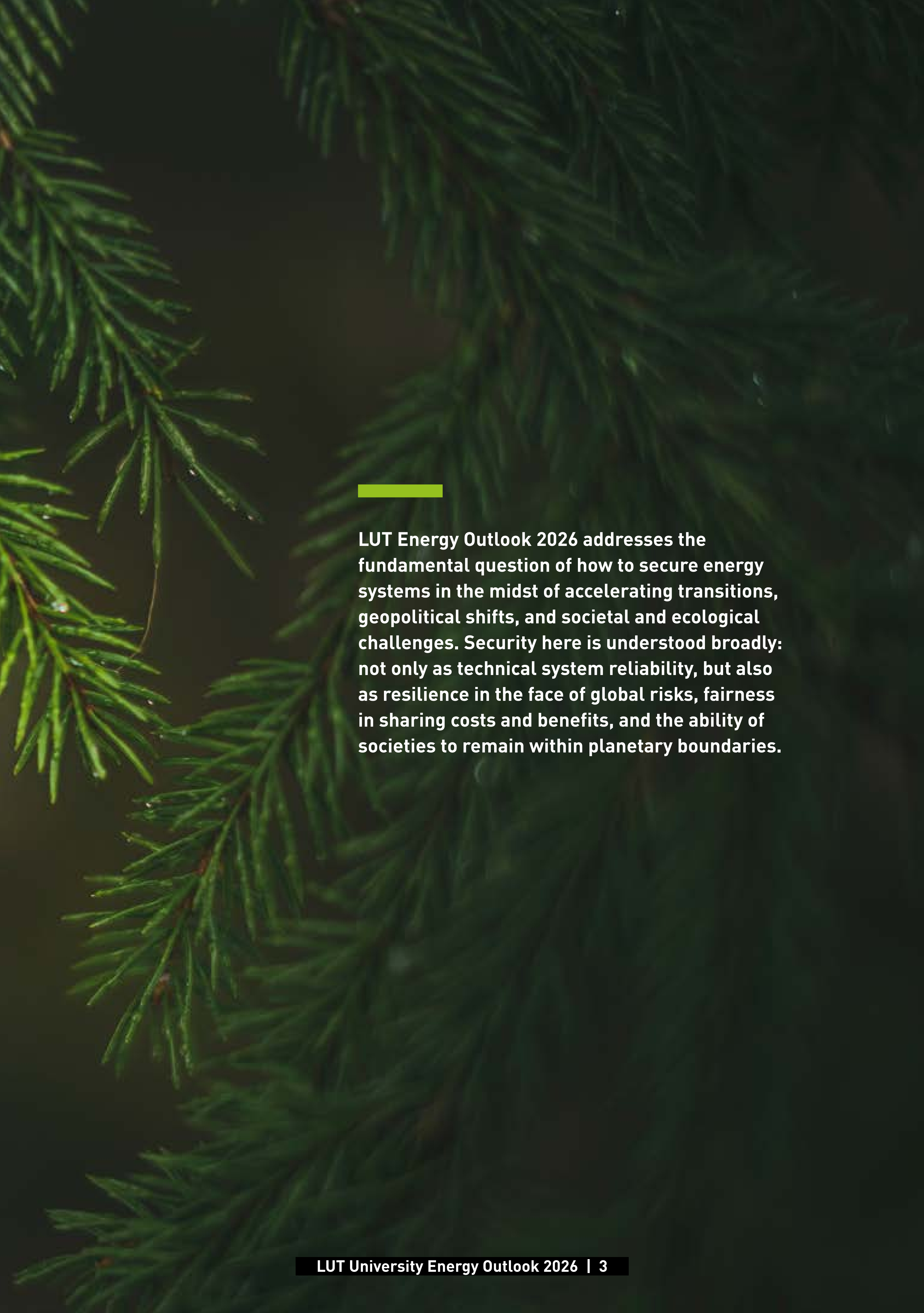
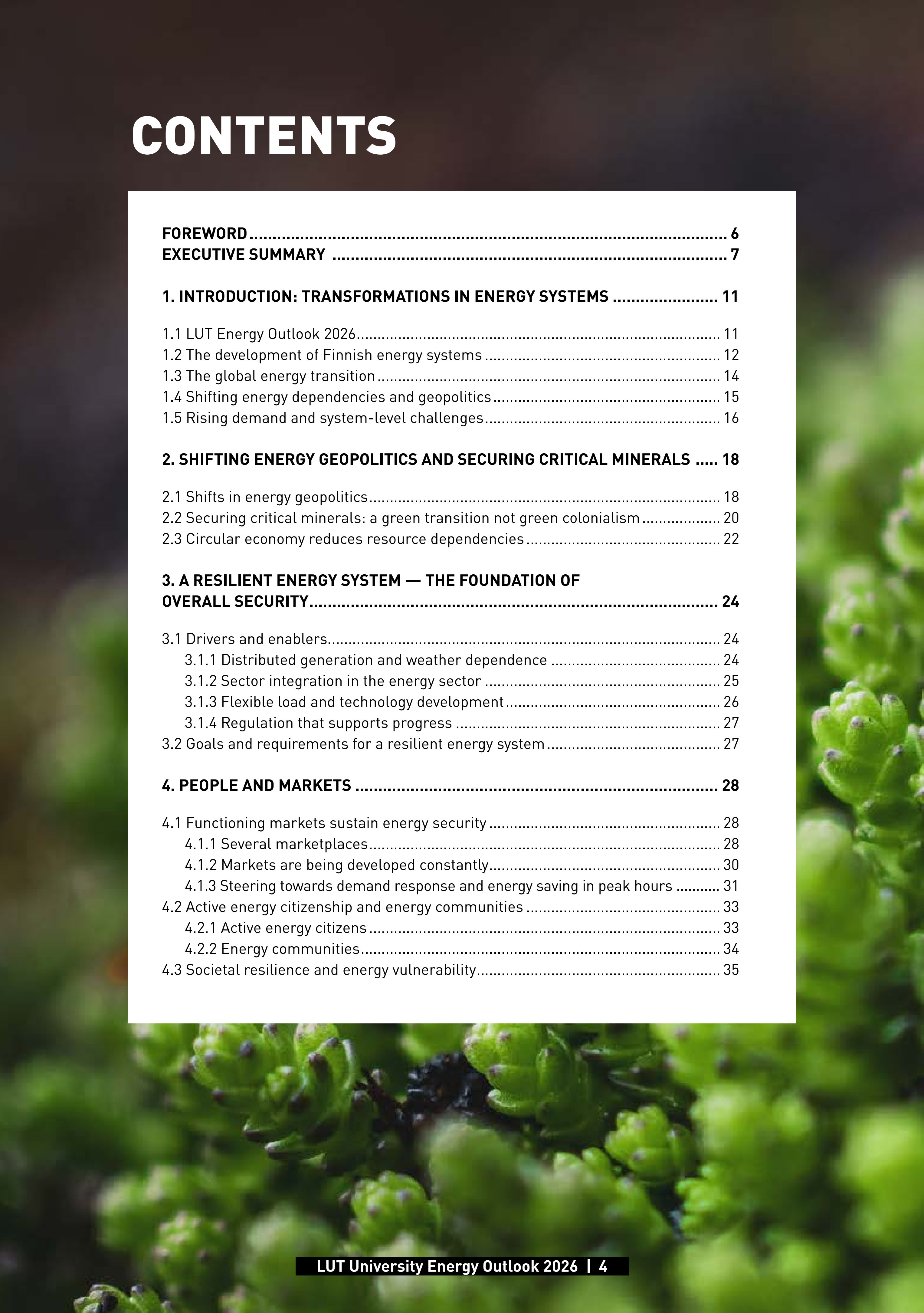


LUT Energy Outlook 2026 addresses the fundamental question of how to secure energy systems in the midst of accelerating transitions, geopolitical shifts, and societal and ecological challenges. Security here is understood broadly: not only as technical system reliability, but also as resilience in the face of global risks, fairness in sharing costs and benefits, and the ability of societies to remain within planetary boundaries.



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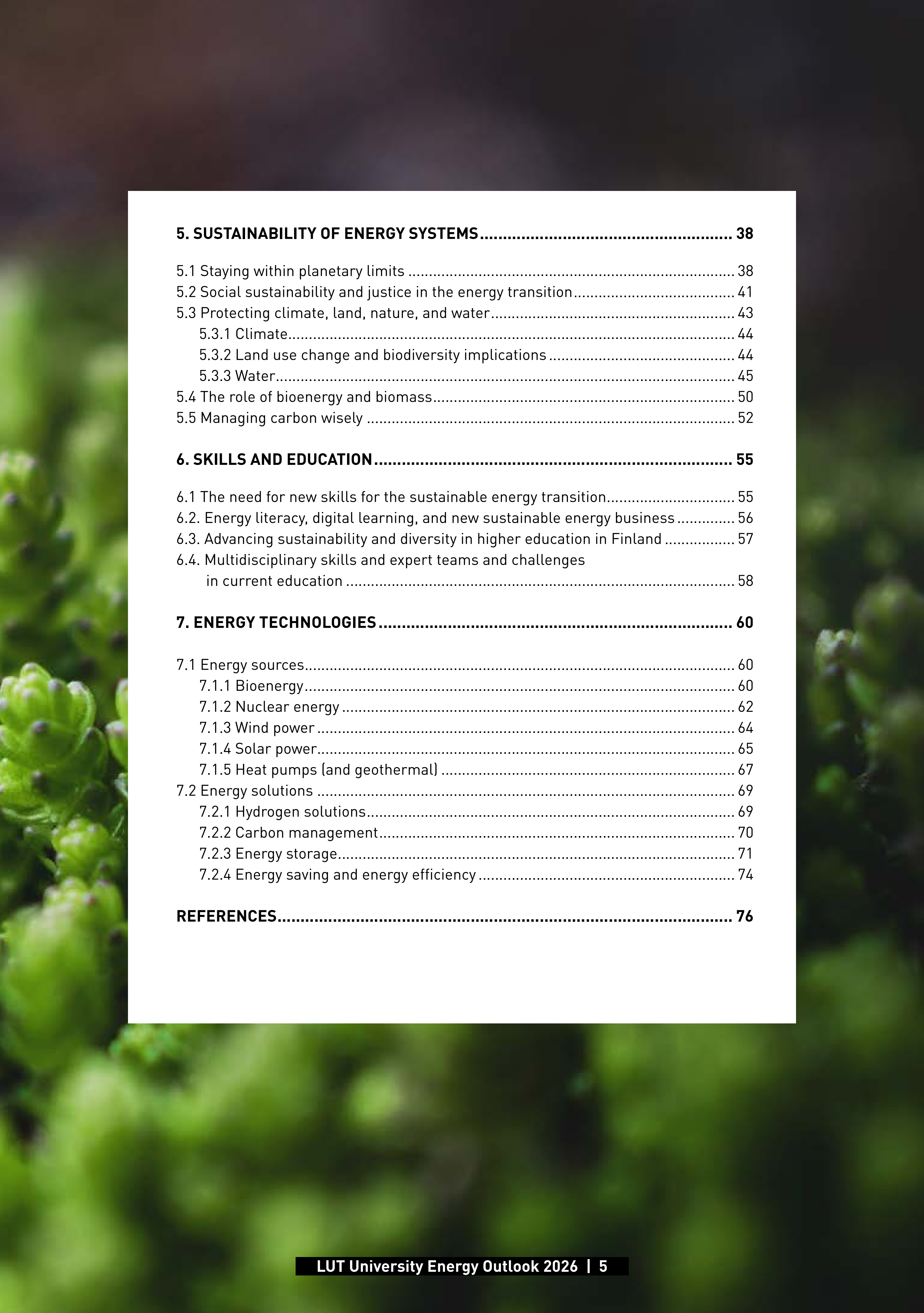


FOREWORD

Finland's energy transition is already well underway, accelerated by the systemic development of the country's energy systems and investments in fossil-free energy sources. As a result, Finland has moved towards an almost fossil-free electricity system, which creates the conditions for a broader sustainability transition and the clean, competitive development of industry. The new system brings opportunities but also new kinds of challenges and vulnerabilities.

As the energy transition and electrification advance rapidly, the interconnections and dependencies between different systems are increasing. The expansion of variable electricity generation poses challenges related to electricity prices and grid capacity, and the social and environmental impacts of renewable electricity production are becoming more pronounced across regions as land use changes. Moreover, the energy transition is a societal transformation, in which new ways of operating—such as active energy citizenship and companies' investments in clean energy—are becoming more common.

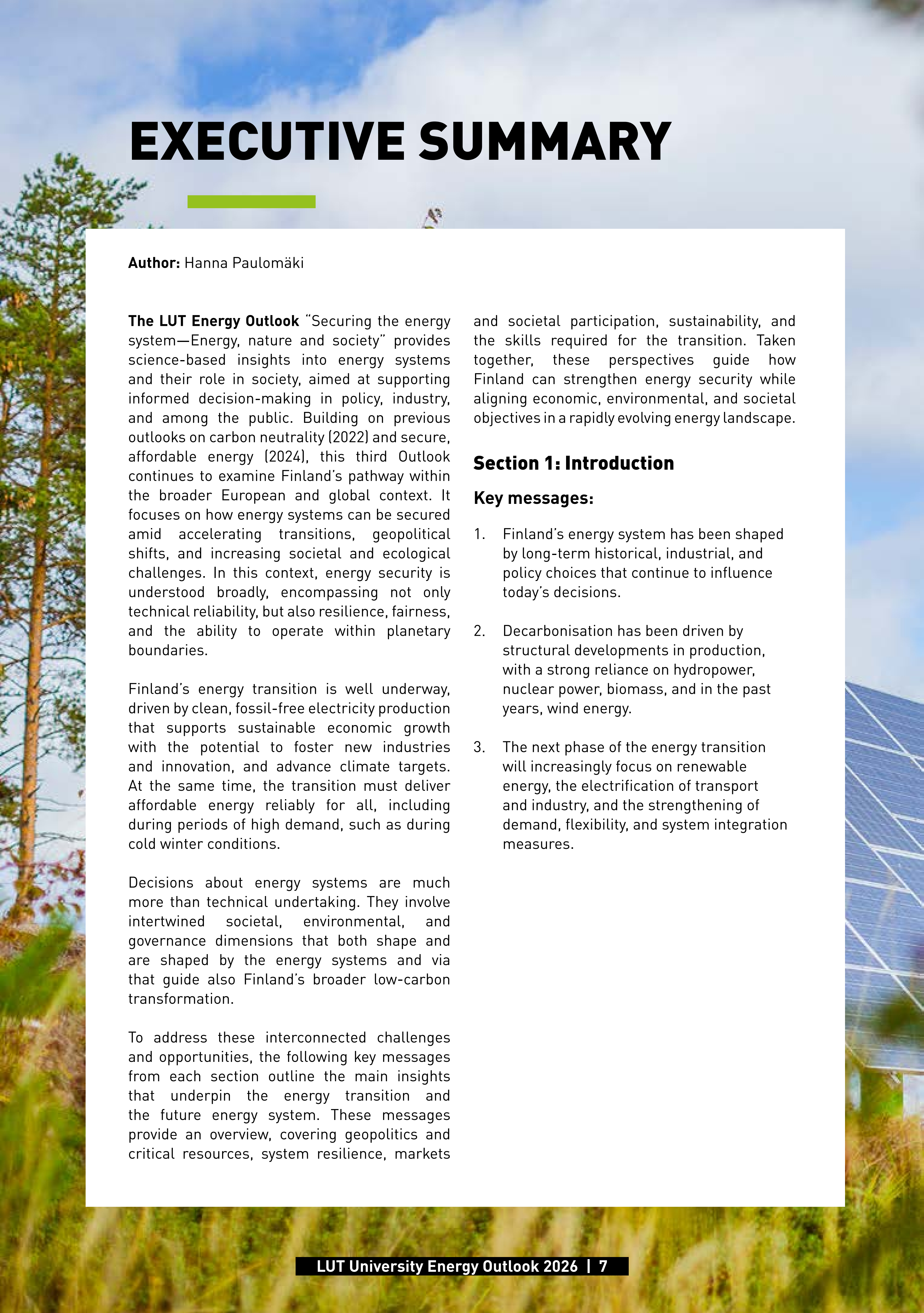
We are once again in the midst of a geopolitical energy crisis, as the war in Iran is severely disrupting global gas and oil trade. Beyond the human cost of war, rising living costs are increasing vulnerability and energy poverty. We have entered an era of polycrisis: the climate crisis is the greatest challenge, the world political order is changing rapidly, and biodiversity loss is accelerating both in Finland and globally.

In this changing and uncertain operating environment, securing our energy systems is vital to the functioning of society. In LUT University's third Energy Outlook, we therefore focus on how we can safeguard our energy system now and in the future, maintaining and strengthening its resilience and ensuring that individuals and communities benefit and gain greater agency. To support sustainable development, we must also strive to minimise impacts on nature and operate within planetary boundaries.

LUT University's Energy Outlook offers a wide range of perspectives and solutions to these challenges. As energy systems become more complex, the need for clearly presented, research-based knowledge grows. In keeping with the third mission of universities—societal impact—LUT University's experts use the Energy Outlook to provide up-to-date knowledge on the development prospects, challenges, and opportunities of energy systems.

The Energy Outlook is intended for experts, policymakers, and ordinary citizens alike. A comprehensive understanding of the overall system is particularly important when steering energy policy, as it enables the balanced development of the whole rather a narrow focus on individual solutions.

Olli Pyrhönen, Dean
Eeva-Lotta Apajalahti, Associate Professor
LUT School of Energy Systems



EXECUTIVE SUMMARY

Author: Hanna Paulomäki

The LUT Energy Outlook "Securing the energy system—Energy, nature and society" provides science-based insights into energy systems and their role in society, aimed at supporting informed decision-making in policy, industry, and among the public. Building on previous outlooks on carbon neutrality (2022) and secure, affordable energy (2024), this third Outlook continues to examine Finland's pathway within the broader European and global context. It focuses on how energy systems can be secured amid accelerating transitions, geopolitical shifts, and increasing societal and ecological challenges. In this context, energy security is understood broadly, encompassing not only technical reliability, but also resilience, fairness, and the ability to operate within planetary boundaries.

Finland's energy transition is well underway, driven by clean, fossil-free electricity production that supports sustainable economic growth with the potential to foster new industries and innovation, and advance climate targets. At the same time, the transition must deliver affordable energy reliably for all, including during periods of high demand, such as during cold winter conditions.

Decisions about energy systems are much more than technical undertaking. They involve intertwined societal, environmental, and governance dimensions that both shape and are shaped by the energy systems and via that guide also Finland's broader low-carbon transformation.

To address these interconnected challenges and opportunities, the following key messages from each section outline the main insights that underpin the energy transition and the future energy system. These messages provide an overview, covering geopolitics and critical resources, system resilience, markets and societal participation, sustainability, and the skills required for the transition. Taken together, these perspectives guide how Finland can strengthen energy security while aligning economic, environmental, and societal objectives in a rapidly evolving energy landscape.

Section 1: Introduction

Key messages:

1. Finland's energy system has been shaped by long-term historical, industrial, and policy choices that continue to influence today's decisions.

2. Decarbonisation has been driven by structural developments in production, with a strong reliance on hydropower, nuclear power, biomass, and in the past years, wind energy.

3. The next phase of the energy transition will increasingly focus on renewable energy, the electrification of transport and industry, and the strengthening of demand, flexibility, and system integration measures.

Looking ahead, the focus is increasingly shifting towards energy demand, system flexibility, and integration. Electrification across sectors, the emergence of new large-scale electricity users, and growing variability in renewable generation are reshaping system dynamics. Addressing these requires a more integrated approach to energy system development, balancing technological, environmental, and societal considerations.

Section 2: Geopolitics and critical minerals

Key messages:

1. The energy transition is reshaping global power structures.

2. Critical minerals and supply chains create new dependencies and strategic risks.

3. Circular solutions and responsible resource use support long-term sustainability and security.

Energy has long played a central role in geopolitics, historically shaped by the concentration of fossil fuel resources. Currently, this can be seen in the Middle East where the recent conflict has exposed the risks of fossil fuel dependence, likely to maintain high energy prices, and accelerating the shift toward renewables, nuclear power, and electrification. Along with the global energy system transitions toward low-carbon solutions, these power structures are being reconfigured, with different regions pursuing distinct strategies and priorities. The European Union has strengthened its focus on energy security and competitiveness in response to geopolitical developments.

Critical minerals such as lithium, cobalt, nickel, and rare earth elements are essential for the energy transition, increasing global competition, and introducing new dependencies. Supply chains are highly concentrated, particularly in processing and manufacturing, which creates vulnerabilities and challenges related to transparency and sustainability. Expanding extraction activities also raise environmental and social concerns, that require focusing on the development and implementation of responsible governance practices, guided by regulatory frameworks, and transparent stakeholder engagement to ensure sustainable and equitable outcomes.

Finland's domestic mineral resources offer potential to strengthen self-sufficiency and supply security, but their development must be carefully balanced with environmental protection and land-use considerations. More efficient material use, recycling, and broader resource efficiency play a key role in reducing the reliance on primary extraction and supporting long-term sustainability.

Section 3: Resilient energy systems

Key messages:

1. A resilient energy system is essential for society's security and functioning.
2. The energy transition brings major benefits but also new vulnerabilities.
3. Energy system resilience requires coordinated flexibility, domestic capability, and supportive regulation.

Electricity is the backbone of our society, enabling critical services such as healthcare, transport, communications, industry, and security. As society becomes more electrified, the ability of the energy system to function reliably under all types of conditions becomes increasingly important. This makes resilience a central requirement for both everyday life and crisis situations.

Rapid growth in wind and solar, sector coupling (hydrogen, PtX), the electrification of heating and transport, and the expansion of data centres are all reshaping energy system behaviour. These developments reduce emissions and improve self-sufficiency, but also increase weather dependence, uncertainty, and pose new operational and cybersecurity risks.

Ensuring resilience in this evolving environment requires coordinated action. Resilience depends on flexible demand, distributed resources, advanced automation, and the ability to form independent regional "islands" when needed. Strengthened domestic energy sources and expertise reduce external risks. Regulation must enable these changes to support long-term grid and capacity development and new operating models while safeguarding reliability.

Section 4: People and markets

Key messages:

1. Markets and price signals support the efficient operation and development of the system.
2. Electrification is reshaping demand and supply patterns.
3. Energy communities offer more active ways for people to participate in the energy transition.

Energy markets play a central role in guiding investments and system operation through price signals that support efficiency and balance. Wholesale market pricing ensures that least-cost energy forms are used and gives positive signals for new investments. Dynamic pricing mechanisms help align supply and demand, and curb price-based energy behaviour.

Electrification is increasing electricity demand and changing consumption patterns. New types of electrical loads, such as electric vehicles and data centres, are increasing the grid load and creating new requirements for infrastructure and flexibility. Furthermore, new power-based tariffs for small-scale customers are being introduced to share network costs more equally.

At the same time, the transition is becoming more participatory. Citizens, communities, and prosumers are taking a more active role in energy production and consumption. This enhances system flexibility but also requires attention to fairness, inclusion, and access, as well as a need for skills and capabilities for people to participate. More democratic and distributed systems reduce energy vulnerability and increase societal resilience.

Section 5: Sustainability and planetary boundaries

Key messages:

4. The energy transition should support a shift towards keeping human activities within planetary boundaries while creating more social justice.

5. Climate and nature should be managed through integrated solutions that also inform and guide land-use planning.

6. Carbon management plays a central role in supporting the sustainable energy transition.

The energy transition provides a central pathway for bringing human activities back within planetary boundaries by enabling a shift toward low-emission energy systems. The planetary boundaries framework defines the safe operating space for humanity, encompassing climate stability, biodiversity, land systems, and water resources. Importantly, climate mitigation efforts need to be implemented in ways that avoid creating new, harmful environmental impacts.

Expanding the energy infrastructure and related industrial activity requires careful planning to minimise ecological harm and manage trade-offs between different environmental objectives, while also addressing societal considerations. Inclusive and just decision-making, involving a broad range of stakeholders, is essential to ensure social acceptance and prevent opposition that could become a major barrier to renewable energy projects.

Carbon management plays a central role in supporting sustainability. This includes phasing out fossil carbon while using biomass sustainably. Complementary solutions such as carbon capture, utilisation, and storage, as well as Power-to-X technologies, support the development of low-emission systems, and enable the more efficient use of carbon.

Section 6: Education and skills

Key messages:

7. The energy transition requires a larger, more diverse, and sustainability-oriented workforce.

8. Education systems should evolve to equip learners with the skills, knowledge, and critical thinking needed to address complex societal, environmental, and technological questions.

9. Future professionals need skills to navigate and drive system-wide transformations.

The energy transition is transforming labor markets and increasing the demand for a broader range of skills. Alongside strong core technical expertise, the transition requires professionals who also have a broader understanding of the environmental and societal dimensions of energy systems.

Education systems need to be developed to meet new demands by updating curricula, strengthening collaboration between academia and industry, and integrating sustainability across disciplines. Broader access to education and training is also essential to enable participation from diverse groups.

Future professionals will need the ability to work across disciplines and manage complexity. In addition to technical knowledge, skills such as systems thinking, communication, and stakeholder engagement are increasingly important for navigating the transition and developing solutions.

1. INTRODUCTION: TRANSFORMATIONS IN ENERGY SYSTEMS

Authors: Hanna Paulomäki, Eeva-Lotta Apajalahti, Juhani Hyvärinen, Ayesha Sadiqa and Esa Vakkilainen

1.1 LUT Energy Outlook 2026

The energy transition in Finland is already well underway. Having fossil-free electricity production provides a strong foundation for economic activities built around clean and renewable energy sources, enabling new industries, investments, and value creation while supporting the broader transition toward a low-carbon society. At the same time, this positive development brings up new questions to be solved. For example, how can clean and affordable energy be ensured for all, even during harsh, dark winter periods? Which emerging pathways should we choose to follow to build future energy systems, and how should the transition itself be governed? This includes determining who sets the direction, through which policies and market frameworks, and what roles public authorities, private actors, and citizens should play in the transition. Many challenges of the energy transition are not only technical in nature but deeply societal and environmental, with impacts that extend well beyond the energy sector and shape society and everyday life.

LUT Energy Outlooks seek to provide science-based insights on energy systems and communicate them in a way that supports decision-making in society. In doing so, we seek to advance understanding, inform experts, policymakers and private actors, and contribute to the discussions with significant societal relevance concerning the energy transition. LUT Energy Outlooks also functions as a platform for the extensive energy research carried out at LUT University by drawing on the expertise of our top energy researchers.

The current Energy Outlook 2026, Securing the energy system—Energy, nature and society, builds on previous versions of the LUT Energy Outlook, which addressed carbon neutrality (2022) and secure, sustainable and affordable energy (2024). In this edition, we examine how energy systems can be secured in a period of rapid transition, geopolitical changes, and growing environmental and societal concerns. Security is understood broadly: not only as technical reliability, but also as resilience to global risks, fairness in distribution of costs and benefits, and the ability to operate within planetary boundaries.

The Outlook explores these themes through several perspectives, including geopolitical and circular economic views, system resilience, market dynamics and citizen participation, and a broad sustainability analysis on the relationship between energy systems, natural systems and societal sustainability. It also provides an overview of key energy technologies and solutions enabling the ongoing transition.

1.2 The development of Finnish energy systems

Finland's current energy system is the result of long-term structural development shaped by industrialisation, energy policy choices, and evolving resource use. This section briefly outlines the key developments that have shaped the transition towards a low-carbon energy system. Looking back helps to understand how today's energy mix, infrastructure, and institutions have evolved, and why certain pathways have been prioritised over others. Decisions made decades ago continue to influence how the system functions and what options are available today.

Eastern Finland can be considered as a cradle for electrifying Finland. Electricity generation and transmission on a national scale began in Finland in the late 1920s with the construction of the Imatra hydropower plant and the construction of the first 110 kV transmission line across southern Finland all the way to Turku. The Imatra power plant had a maximum output of 120 MW, which, if operated at full capacity would have exceeded national consumption at the time. The significance of the Imatra power plant is clear; it supplied over 90% of Helsinki's electricity for four decades. By comparison, Finland's average electricity demand in the 2020s has stabilised at around 10,000 MW annually—about 80 higher than a century ago.

In the 1940s, territorial losses to Russia cost Finland two thirds of its hydropower capacity. In the postwar decades of 1950–1970 electricity consumption grew steadily, driven largely by the forestry and metal refining industries, as well as the increasing use of household electrical appliances. Nation-wide 220 kV and later 400 kV lines were built both by state-owned Imatran Voima and other major industrial companies, bringing hydropower from the northern regions to southern Finland.

The construction of nuclear power plants started in the mid-1970s and four units, two in Loviisa and TVO in Olkiluoto, started to operate in 1978–1981. At that time, energy policy decisions were based on economic considerations but also on geopolitical pressures, however, maintaining a balance between the East and West—nuclear technology was imported both from the East (Soviet Union, adapted to meet Western safety standards) and the West (Sweden). The first undersea cable linking Finland and Sweden was completed in 1989. Cross-border transmission links both to East and West were built, mainly to enable electricity imports during peak demand.

Large coal-fired power plants were added to back up four nuclear power plants as well as to secure thermal power and ensure the cogeneration of electricity and heat. Rapid expansion of the district heating network, which was built across Finnish cities and towns from the 1960s to 1980s, was a major systemic change for existing small-scale detached heating. Municipal cogeneration power plants jointly owned by local large industrial facilities were initially fuelled with biomass, coal and peat, an later on by natural gas. Although the construction of the natural gas pipeline connection with the Soviet Union started in the1970s to provide additional options after the Oil Crisis, large-scale natural gas plants for cogeneration were built later in the 1990s. The expansion of the pulp and paper industry and rapid expansion of district heating increased the use of biomass with pulping residues burned in industrial cogeneration plants to run the mills and supply local heating.

The commissioning of nuclear power in the early 1980s had a profound, yet unintended, impact on Finnish greenhouse gas emissions. The specific carbon dioxide output from electricity generation dropped nearly fourfold, from a peak of 450 gCO_2/kWh(e) in 1975 to less than 120 gCO_2/kWh(e) in 1982. By the mid-1980s, the share of nuclear power was around 37% of the total electricity consumption, making it the largest source of fossil-free electricity.

Finland joined the EU in 1995, and set the Energy Market Act the same year, which reshaped the power industry by separating electricity grid operators from production and sales, thus opening electricity supply to competition. Fingrid was established as the national transmission system operator in 1997 and Finland joined the common Nordic electricity market, Nord Pool. Since 1998 electricity end-users have been able to choose their electricity provider, while district heating has remained a local monopoly.

From 1980 to 2007, electricity consumption in Finland grew steadily by about 2 TWh per year, reaching a peak of 90 TWh in 2007. Carbon dioxide emissions from electricity generation rose to 300 gCO_2/kWh(e) by 2003, then declined rapidly to 100 gCO_2/kWh(e) by 2015, driven by increased biomass use in municipal cogeneration plants and relatively high electricity imports. Since 2007, the total electricity consumption has remained stable between 80 and 87 TWh, but this masks important shifts: industrial consumption, particularly in the forestry sector, fell by 12 TWh between 2007 and 2025, while non-industrial demand grew by 6 TWh. Seasonal variation remains significant, with differences between summer and winter demand reaching 10–15 TWh annually (Fingrid, 2024a; Statistics Finland, 2024).

Wind power in Finland took off after feed-in tariffs were introduced in 2010, when the installed wind capacity was just 196 MW. By 2018, the installed capacity had climbed to 2,000 MW—an almost fivefold increase in just seven years—while the feed-in tariff was closed for new projects. By 2025 wind had become Finland's second largest form of electricity production, producing 22 TWh from 9,433 MW of installed capacity and accounting for 26% of Finland's electricity consumption. Solar power has also been expanding rapidly. In 2025, seven new utility-scale solar plants were completed in Finland, adding 227 MW of capacity. By the end of the year 2025, the total installed utility-scale solar capacity reached approximately 352 MW, and the total installed capacity amounted to 1,512 MW (Fingrid, n.d.). This rapid growth demonstrates that solar power can now be deployed at an industrial scale even in northern conditions.

The commissioning of Olkiluoto 3 in 2023 brought the nuclear energy share of electricity generation to 37% of the total national electricity production, which cut CO_2 emissions by almost half from 2022 to 2023. In 2025, the total electricity production in Finland was 80 TWh, of which the share of renewable energy was 55%, and 98% of the produced electricity was fossil-free (Statistics Finland, 2024). In electricity production, nuclear power generated 32 TWh, the second largest sources being wind 22 TWh, hydro 13 TWh and bioenergy 78 TWh (Statistics Finland, 2024).

District heating in Finland has rapidly moved away from fossil fuels during the 2020s. Peat use has dropped to one-fourth, and the last major coal-fired facility in Helsinki's Salmisaari plant was closed in April 2025 in line with the 2029 coal ban. Modern district heating increasingly relies on biomass, municipal and industrial waste, waste heat recovery, large-scale heat pumps, and electricity, with electric boilers and thermal storage contributing 2.6 TWh of the total 35 TWh in 2025.

Finland has reached a major milestone on its decarbonising path: electricity production is now almost completely fossil-free and CO_2 emissions have decreased dramatically over the past decade (See Figure 1.1). This achievement is built on investments in nuclear, wind and hydropower, backed by strong political will and decisive fossil phase-out policies.

Finland's low-carbon electricity system reflects decades of structural development, including early investments in nuclear power, industrial transformation, and a lack of domestic fossil fuel resources. Nuclear power remains a cornerstone of fossil-free electricity generation, whereas near future electrification will be driven primarily by solar and wind power, which is expected to continue growing strongly. Today, rapidly growing renewables, electrification, and new large-scale users such as data centres and hydrogen production will shape the energy system by increasing the electricity demand and requiring more system integration and optimisation. The growing share of variable electricity production and periods of low-cost electricity need greater flexibility through demand response, storage, and adaptable capacity. Strengthening these elements will be key to maintaining system reliability, supporting continued decarbonisation, and capturing the full benefits of Finland's evolving energy system.

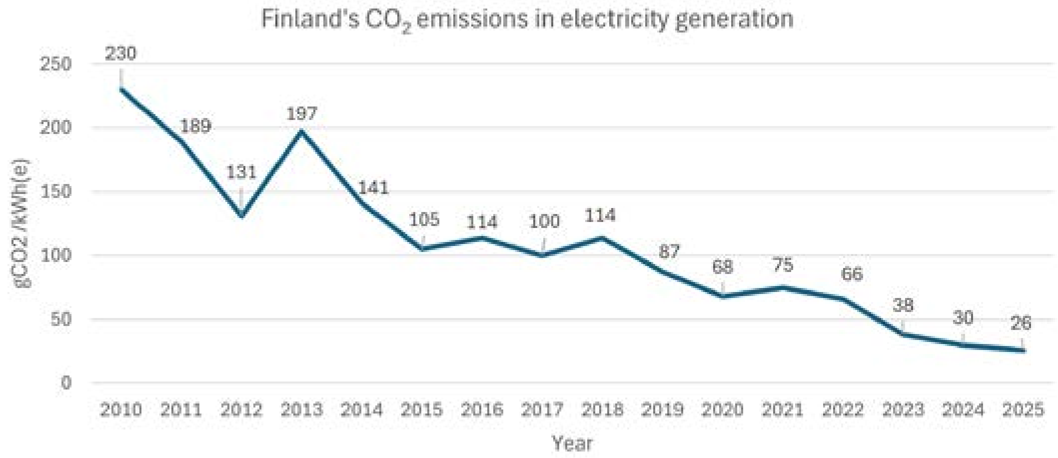


Figure 1.1 Finland's CO2 emissions per produced kWh 2010-2025 (Finnish Energy, 2025).

1.3 The global energy transition

Energy systems are developing constantly, a new focus at the moment being on electricity-based decarbonising efforts in heating and transportation (so called sector coupling), increasing low-carbon electricity generation and new investments in electricity-using industry and related energy products. These directions are tightly linked with global energy transitions, which are accelerating in Finland, Europe, and globally, shaped by a combination of geopolitical developments, technological progress, and changing economic and societal priorities.

We are in a fragmented, multi-speed energy transition. Progress will continue, but different regions are placing different levels of priority on clean energy development, and technologies are scaling at different speeds. The major global economies face new strategic considerations, and climate mitigation no longer seems the shared priority it once was. The UK and EU have each set new Paris-aligned emissions goals for 2035, which will require significant efforts to achieve. China's new target is a step forward, as for the first time it calls for the country's emissions to decline. In contrast, the US's NDC, released in the last days of the Biden administration, is now effectively null and void (the US is exiting the Paris Agreement) (Cheung, 2026; IEA, 2026a).

In 2024, globally more than 90% of the new power capacity added came from renewables, and the trend was similar in 2025 (IRENA, 2025a). At the same time, the levelized cost of electricity (LCOE), representing the average cost of electricity generation over a plant's lifetime, is lower for variable renewables than for conventional power generation technologies (IRENA, 2025b), however, electricity production from fossil fuels is still expanding. This highlights the need to find economic solutions to manage large shares of variable electricity production and managing variable production slumps. International renewable power capacity has consistently increased faster than projected by the International Energy Agency (Lopez et al., 2025), and furthermore, financial assumptions in energy scenarios are regularly too conservative compared to market realities (Vatankhah Ghadim et al., 2025). This holds particularly for solar PV, which has been the single fastest growing source of electricity for years contributing about two-thirds to all globally added power capacity across all technologies (IRENA, 2026), thus constantly exceeding what has been projected.

The energy transition in the EU is no longer a climate initiative, it has become a strategic necessity for security, economic competitiveness, self-sufficiency, and resilience. The EU has implemented various policies which aim to reduce fossil fuel consumption. It has set the target that 42.5% of its energy should come from renewable sources by 2030. Currently EU fossil fuel imports account for 58% of its total primary energy consumption, leaving it as one of the most exposed regions to market fluctuations and geopolitical turbulences. The largest energy exports to the EU were Norway (15% of petroleum and 51% of natural gas) and the US (58% of LNG), while Russia's shares have constantly declined and will further decline as a result of the 19th sanctions package (IEA, 2025a).

Global sustainability and decarbonisation efforts have resulted in tangible gains in the deployment of energy technologies and improvements in energy efficiency. To date, 77% of the economies have, net-zero targets, either proposed or legalised. A report by Barth et al. (2026) explored the reality gap between the deployment of eight key decarbonisation technologies (wind onshore and offshore, solar, batteries, nuclear, hydrogen, sustainable fuels, EVs) and their 2030 targets set by Europe and the United States. The data suggests that these regions are missing their decarbonisation targets. Not only is the priority landscape shifting, but the geopolitical environment is also now more unpredictable, which can impact the pace of the energy transition significantly. With increasing defence budgets and uncertainty from tariffs on imports, fewer resources may be available for decarbonisation on a national level, while tariffs could lead to inefficient global supply chains, potentially slowing efforts to transition to cleaner energy.

1.4 Shifting energy dependencies and geopolitics

Energy has long been a source of geopolitical influence, with fossil fuel resources concentrated in a limited number of countries. This has shaped and still continues to shape global dependencies and the political influence of countries. This became evident following the Israel and US strikes on Iran at the end of February 2026, which heightened geopolitical uncertainty in the Middle East. In particular disruptions in the Strait of Hormuz—through which roughly one-fifth of global oil supply passes—has led to a near halt in the shipping temporarily due to the risk of attacks. The conflict has triggered a major fossil fuel supply shock, reinforcing the risks of oil and gas dependency and likely sustaining high energy prices. In response, many countries are expected to accelerate efforts to reduce their import reliance, increasing the strategic importance of renewable energy, nuclear power, and electrification.

The transition away from fossil fuel-based systems is on-going, which can change the geopolitical environment rapidly. While renewable energy-based systems are changing the old geopolitical conflicts, new dependencies are emerging.

Currently, there are increasing disparities in the major economies' energy strategies, and the pursuit towards renewable energy systems are not as aligned as few years earlier. The United States and Russia continue to rely on fossil energy to maintain their geopolitical leverage, although renewable electricity is expanding rapidly, particularly in the United States. China, in contrast, is reducing fossil energy dependency through large-scale investments in wind and solar power, enabling it to meet growing electricity demand increasingly with clean energy. The European Union has reframed the energy transition as a matter of security and competitiveness, accelerating its shift away from fossil fuel imports following Russia's invasion of Ukraine in February 2022. The shift has been significant; for the first time in 2025, wind and solar power surpassed fossil fuels in EU electricity generation.

Expanding the production of fossil-free and renewable electricity is enabling the ongoing electrification of industry and the replacement of fossil fuels and feedstocks in the heating and transport sectors. In Finland, industrial electrification could multiply its electricity consumption, particularly if the country captures its export potential in electricity-based products such as fuels, chemicals, and materials. This requires large-scale investments also in batteries (for EVs and electricity) and other storage technologies. This shift creates new kinds of dependencies and changes the geopolitical environment.

New dependencies, for example in the EU, are related to global supply chains of solar PV and wind turbine technologies, as well as critical minerals (see Section 2 on new geopolitics). China has control over all these supply chains. It now produces more than 70% of the world's solar modules and hosts nearly half of the world's wind turbine manufacturing capacity. China has also a dominant position in both the production and processing of rare earth minerals and controls a substantial share of relevant global supply chains. For example, China is now the dominant supplier of 23 metals deemed critical by the European Commission. In the battery sector, the EU sources 37% of raw materials from China (vs. 2% domestically), 72% of processed materials (vs. 4% from the EU), 67% of components (vs. 3% from the EU), and 75% of assemblies (vs. 6% from the EU) (Carrara et al., 2023).

Overall, Finland is well positioned in the ongoing transition due to its largely fossil-free electricity production, strong grid, competitive electricity prices, and sparsely populated land providing prospects for renewable energy production. In addition, access to biogenic carbon dioxide from the forest industry enables the production of synthetic fuels and chemicals. Furthermore, Finland also provides a possibility for the EU to reduce its dependency on China, as amongst EU countries, Finland has unique deposits of all the key battery minerals. Finland also already has a long history in mining and refining, therefore possessing advanced refining capabilities and a skilled workforce, with a strong focus on research and collaboration. This creates several new industrial pathways for Finland, however, also introducing new trade-offs related to resource availability and environmental impacts. These factors place Finland within broader global shifts where energy, industry, and geopolitics are increasingly intertwined and shaped by both technological progress and political and strategic choices.

1.5 Rising demand and system-level challenges

The implementation of the energy transition in Finland comes with interconnected challenges related to energy systems, resources, environment, and societal sustainability, while also enabling new solution pathways.

A central challenge is the rapid growth and changing profile of the electricity demand. The increasing use of variable renewable electricity, electrification of industry, heating, and transport, coupled with increasing data centre demand, will increase consumption while altering load patterns, leading to higher peak loads and greater variability. This requires investments in reserve capacity and flexibility, increasing the attractiveness of demand response, as well as improved balancing of variable renewable generation. The challenge becomes more pronounced acknowledging that the current electricity market does not provide sufficient incentives to build reserve and peak capacity.

System integration and infrastructure form another key challenge. Scaling up renewable energy requires grid expansion and better coordination between the electricity, heating, transport, and industry sectors. Sector coupling (integrating these sectors through electrification and the use of energy carriers such as hydrogen and heat with flexibility opportunities) can improve overall system efficiency and resilience. At the same time, it increases the system complexity and systemic interdependencies.

Resource constraints may become a limiting factor as the transition progresses. The growing demand for many minerals raises concerns about their availability, sustainable use and circular economy options. At the same time, the expansion of renewable electricity production introduces new types of land use, which calls for a more careful assessment of how land is allocated and how these developments interact with ecosystems and biodiversity.

The energy transition is very much a societal change. Infrastructure projects are always implemented in some regions where it has impact on the lives of local people and communities. Energy projects may face local opposition, as the distribution of costs and benefits raise concerns about fairness and social sustainability. Ensuring a just transition requires the inclusion of local communities in the decision-making and attention to local and regional impacts. The energy transition is therefore a continuous societal process in which technological development, environmental limits, and social values must be aligned.

Building on this context, the LUT Energy Outlook 2026 is a set of interconnected perspectives that shape the transition in practice: geopolitics and the circular economy, system resilience, people and markets, sustainability, and enabling technologies. Together, these perspectives highlight the challenges and solutions involved in securing energy systems in a changing world.

2. SHIFTING ENERGY GEOPOLITICS AND SECURING CRITICAL MINERALS

Authors: Alicja Dankowska, Joni Lappi, Ayesha Sadiqa, Roosa Talala and Eeva-Lotta Apajalahti

2.1 Shifts in energy geopolitics

Energy geopolitics describes how energy interdependences shape countries' position on a global arena and their international power (Overland, 2015). Energy geopolitics have traditionally focused on oil and gas markets. The global dependency on fossil fuels is still strong, with around 80% of the world's energy supply still derived from them (IEA, 2025a), while around 6.9 billion people—approximately 86% of the global population—are living in nations that rely on imported oil, gas, or coal. Oil and fossil fuels, thus still play a major role, although new energy investments in renewable energy and related components exceeded fossil energy for the first time in 2023, and almost doubled in 2025 (IEA, 2025b).

Different fossil fuels are associated with distinct geopolitical dynamics. Oil, along with its availability and distribution routes, has long been at the core of energy geopolitics, whereas coal and gas rely on different transport routes and supplier structures, and therefore face different dynamics. An exception is LNG that use same shipping routes as oil. Major shocks in oil markets are closely tied to geopolitical conflicts, which both influence and are influenced by oil, disrupting supply routes, halting production, and creating uncertainty. The ongoing geopolitical shock due to Israel and US forces attacking Iran at the end of February 2026, has almost completely halted the oil transportation in the Strait of Hormuz, which is an important route used to deliver a fifth of the world oil and natural gas. This has caused oil prices steep increase, creating a global-wide shock, which exists simultaneously with other ongoing war started by Russia's attack in Ukraine.

In addition to the immediate impacts in the affected regions, deaths, terror and insecurity, the current shock is reducing energy security and causing widespread global consequences for economies and the oil and gas industry (DNV, 2026). According to the executive director of the International Energy Agency Fatih Birol, the ongoing war in Iran has more severe impacts globally than past shocks of the 1970s and the effect on gas markets of the Russia–Ukraine war (Euronews, 2026). The impacts are not confined to Iran only; the war has severely damaged more than 40 critical assets in nine countries in the region (DNV, 2026).

The shock is directly impacting the oil and gas industry, as well as oil- and gas-using heavy industries, fertiliser industries, aviation and road transportation. Furthermore, inflation and interest rates are increasing, thus impacting all investments. Countries are impacted by the current crisis in different ways. While low- and medium-income countries are most vulnerable to the shock because they cannot afford rising prices (DNV, 2026), Russia benefits from the disruption, because Russia's routes have not been as affected, and while the oil prices keep rising, more income flows to Russia. Furthermore, due to the halting imports of energy resources from Russia, Europe has turned towards LNG, which is now affected by the current war in Iran. However, the shock has shown some positive impacts on the Chinese battery manufacturing industry (DNV, 2026), thus directing the focus towards the energy transition.

Shocks and crises related to fossil energy sources are expected to speed the shift towards renewable energy sources. While raising interest rates has a negative impact on new investments, the current crisis is expected to benefit renewable energy, the battery industry and the introduction of nuclear power (DNV, 2026). The global expansion of renewable energy is thus reshaping the global power dynamics, and redefining which states stand to gain or lose from the energy transition. Fossil fuel exporting countries will eventually face declining revenues, while new opportunities arise in clean energy sectors. This puts regions in different positions, for example late-exit producers whose oil and gas market shares may temporarily grow (e.g. Gulf petrostates), vulnerable exporters face revenue declines (e.g. Nigeria), and potential winners with abundant clean resources (e.g. Iceland) will gain.

Transitioning towards renewable energy-based systems can reduce import dependence and can address climate change through decarbonisation, but at the same time it is anticipated to lead to shifting power dynamics globally (see, for example, IRENA, 2024a), and the expected gains and losses are already shaping national strategies and international tensions. For example, the strategic dilemmas facing the EU—highlighted in Mario Draghi's 2024 report (EU, 2024)—underscore the challenging balance between advancing necessary decarbonisation efforts and managing the resulting dependencies on low-cost imports from China, alongside growing pressures on economic competitiveness. In spite of the dilemma, the shift towards renewables-based energy systems can mitigate major risks associated with dependence on fossil fuels, providing countries with greater energy autonomy.

Historically, the supply of fossil fuels has been deeply shaped by geopolitical dynamics, with centralised infrastructure prone to disruption and fuel prices exhibiting high volatility. Expanding renewables can therefore reduce exposure to the weaponisation of fuels, market manipulation, interruptions in long-distance supply chains, and environmental hazards such as oil spills (IRENA, 2024a). However, the clean energy transition introduces new geopolitical risks, with two major ones relating to access to critical minerals and cybersecurity threats (Vakulchuk et al., 2020). In this context, we can speak of the "new geopolitics" of energy (Siddi, 2021), in which the acceleration of the transition process depends on access to critical minerals—increasingly referred to as the "new oil." However, the "new" and "old" geopolitics have slightly different dynamics due to the different time-scales of the impacts. Whereas shortages and shocks in fossil fuels directly affect daily energy supply and prices, critical materials for renewable energy technology affect the availability of resources and investments in the planning and construction stages.

A global shift towards renewable energy technologies, including wind power, solar energy and electric vehicle batteries, as well as storage technologies is leading to a significant increase in demand for minerals, including nickel, cobalt, lithium and rare earth materials. Therefore, the global focus has increasingly turned towards the availability, sourcing, and distribution of critical minerals. Minerals have become the "new oil" in the latest frontier of geopolitical and economic competition, triggering a new wave of resource nationalism in producing countries and competition for dominance of the supply chain among major economies (Amineh, 2025). However, whether a shift towards renewable energy reduces geopolitical conflicts because of increasing self-sufficiency or whether geopolitical tensions will remain is still debated by the experts (Vakulchuck et al., 2020).

Currently, China is a leader in securing resources for the energy transition and its Belt and Road Initiative, the huge infrastructure development project by China in many Asian and African countries could consolidate its position (Yiping Huang, 2016). China has a dominant position in both the production and processing of rare earth minerals and controls a substantial share of relevant global supply chains. For example, in the Democratic Republic of Congo (DRC), 15 out of 19 copper–cobalt mines are owned by Chinese companies, and the extracted material largely goes to China, where about 75% of global processing takes place.

Furthermore, China is now the dominant supplier of 23 metals deemed critical by the European Commission. In the battery sector, the EU sources 37% of raw materials from China (vs. 2% domestically), 72% of processed materials (vs. 4% from the EU), 67% of components (vs. 3% from the EU), and 75% of assemblies (vs. 6% from the EU) (Carrara et al., 2023). For Europe, this raises risks of market monopolisation, potential export controls or market manipulation, and a "sustainability black box" that makes it difficult to verify whether minerals are sourced responsibly. This illustrates well the dominant position China holds in the global critical minerals arena.

China is also prominent in renewable energy technology and battery manufacturing. It now produces more than 70% of the world's solar PV modules and hosts nearly half of the world's wind turbine manufacturing capacity. China relies heavily on a limited number of foreign countries for the needed minerals. This dependence makes China's supply chain vulnerable to political and economic policy shifts in those countries, which can disrupt import stability and threaten supply security. Nevertheless, China holds a significant advantage in the processing and refining of most energy transition minerals, commanding a substantial share of the global market. However, growing geopolitical competition and the rise of resource nationalism pose serious challenges to ensuring the security of China's energy transition mineral supply (Amineh, 2025; Vakulchuk, 2020).

The EU has technological manufacturing advantages in terms of wind power, solar energy and electric vehicle batteries, but critical minerals consumption is highly dependent on imports. To enhance the refining, processing and recycling of critical minerals and rare earth metals, the European Commission passed the Critical Raw Material Act in 2024 (EU, 2024/1252). According to the act, in any processing stage, the annual import volume of critical raw materials from a single third country should not exceed 65% of the EU's annual consumption (Amineh, 2025; Wigell et al., 2022).

2.2 Securing critical minerals: a green transition not green colonialism

Over the past 20 years, annual trade in energy-related critical minerals (including lithium, nickel, cobalt, graphite, and rare earths) has increased more than sevenfold, and by 2040, demand for battery minerals is projected to rise 20× for nickel, 19× for graphite, and 14× for lithium compared with 2020 (Carrara et al., 2023). The International Energy Agency warns that supply chains are highly concentrated and vulnerable to geopolitical risk and export controls (IEA, 2023a). Hence, this surge in demand is creating geopolitical supply risks, meaning constraints and bottlenecks that can disrupt steady resource flows (Habib et al., 2016).

Importantly, many mineral-rich countries are in the Global South, where weak governance, corruption, and armed conflicts or wars can heighten the supply risk and complicate responsible sourcing. According to the IEA's Critical Minerals Market Review (IEA, 2023a), three challenges must be addressed to keep the transition rapid and secure: i) ensure future supplies keep up with dynamic demand growth, ii) diversify sources to avoid over-reliance on a few suppliers, iii) guarantee that supplies are clean and responsibly produced.

Example of cobalt—green extractivism?

Cobalt illustrates these dynamics clearly. This critical mineral is essential for lithium-ion batteries, and EVs are the largest end-use sector, accounting for about 40% of the market. Global demand for cobalt has increased from 70,000 tons in 2010 to a projected 250,000 tons by 2028. Yet, the cobalt global supply chains lack diversity: in Europe, only about 2% of global mining and 12% of global refining take place. Most of the world's cobalt, about 73%, is mined in the Democratic Republic of Congo (DRC), which also holds almost half of known reserves. Yet despite this mineral wealth, the DRC remains among the five poorest countries in the world.

Roughly 20% of cobalt in the DRC is extracted in artisanal mines. Artisanal mining often means hazardous, unregulated work: narrow hand-dug shafts, little or no protective gear, frequent injuries, fatal landslides or flooding, and the continued presence of child labour. The environmental toll is also severe: with acid-contaminated rivers, serious health problems in nearby communities, and cases of forced evictions when mines expand. These harms occur amid weak governance and corruption: while extracting companies and state authorities benefit, local communities have little say and bear most costs.

As public awareness has grown, companies and consumers in the Global North have pushed for sustainability and traceability in cobalt supply chains. Critics describe the current model as "green extractivism", where environmental and social burdens are externalised in producer regions while most value accrues elsewhere (Remme et al., 2023). A key turning point was Amnesty International's 2016 report, which documented gross human rights abuses in cobalt supply chains and presented evidence linking Western manufacturers—including VW, Samsung, and Mercedes—to cobalt sourced from sites where children were mining (Amnesty International, 2016).

Following this, EV companies have been urged to deliver an "ethical battery", and due diligence has gained traction as the corporate international human rights standard across the cobalt chain. Initiatives such as the Responsible Raw Materials Initiative emerged to hold major manufacturers accountable and support stronger due diligence and transparency.

Acknowledging the critical material dependency and country dependency, there are ways to reduce both dependencies. Material dependency on cobalt has been partly mitigated by transitioning from NMC to LFP lithium-ion batteries, for which cobalt is not needed. In 2024, lithium iron phosphate (LFP) batteries accounted for nearly 50% of the global electric vehicle (EV) market and around 75% in China, with both shares continuing to grow. This shift is driven by efforts to reduce reliance on cobalt as well as to address challenges in nickel supply (IEA, 2025c). In addition, sodium-ion batteries have been introduced as automotive batteries aiming to even substitute lithium if needed.

To reduce the country dependency especially from China, the EU targets by 2030 are for domestic extraction (10%), processing (40%), and recycling (25%) (EU, 2024/1252). The core goal is to diversify the supply and "not to fall from one dependency into another." Finland, uniquely endowed with all key battery minerals, advanced refining capabilities, fossil-free electricity, skilled workforce, and a strong focus on research and collaboration, is central to these efforts in Europe. The National Battery Strategy aims to make Finland a leader in sustainable battery production by 2025, while the Finnish Minerals Group seeks to build "a solid battery value chain" in Finland (Finnish Battery Industries, 2025). Favourable conditions and public co-investment have attracted interest worth an estimated €6–9 billion and up to 20,000 jobs over the next five years. For instance, Terrafame has partnered with Renault to develop an integrated EV supply chain—from mining and processing to car manufacturing.

However, rapid expansion brings environmental risks and social opposition. Finland has seen leaks that have contaminated freshwater, including the 2012 Talvivaara incident affecting ~1,000 ha (hectares) of rivers and lakes, and the 1990s toxic leak from a cobalt mine into Lake Saimaa. Furthermore, ongoing and contested plans to establish a new nickel and copper mine in the vulnerable and Natura-protected aapa mire of "Viiankiaapasuo" in Sodankylä, in Finnish Lapland, have raised concerns over potentially severe environmental consequences. Hence, new plans to expand mineral and metal mining and processing face strong social resistance, including a citizen legislative initiative, "Limits to mining," brought to parliament. Mining expansion has sparked conflicts especially in nature conservation zones, Sámi reindeer herding territories, tourism and cultural heritage sites, and lake regions with holiday homes (Eerola, 2024). If unaddressed, this opposition could slow the transition, raise costs, undermine net-zero goals, and erode trust and social cohesion.

2.3 Circular economy reduces resource dependencies

Reducing the dependence on conflict minerals and other strategic raw materials can help to mitigate energy conflict risks (Scheffran, 2023). One crucial aspect to reduce this dependency is to increasingly turn towards the circular economy (CE), which has become not only a necessity for society and the economy but also a priority from environmental perspectives (Georgescu et al., 2025).

The circular economy can be defined as a regenerative alternative to traditional linear economic models, based on reducing waste and promoting recycling. CE is aligned with the European Union's (EU) strategic objectives of green and digital transition, which seek to decarbonise the economy and optimise economic flows (Georgescu et al., 2025). Put simply, the key principle in CE is to make the most of available resources and to prioritise cleaner processes and energy systems (Arias et al., 2023).

Within the EU, CE is a central component of the European Green Deal and the Circular Economy Action plan, both aimed at reducing environmental impacts. Across EU Member states, CE takes different forms depending on levels of economic development and the availability of recycling infrastructure (Georgescu et al., 2025). Finland was the first country in the world to develop a national roadmap for CE and all the ministries have since implemented CE strategies aligned with the national target of achieving carbon neutrality by 2035 (Reet al. 2023). CE-related emission reduction measures include the development of cleantech and improved export opportunities, energy savings, and reduced reliance on imported energy (Finnish Government, 2021).

Energy-based industrial symbiosis (IS), where waste streams from one production process are reused in another as a substitute to conventional inputs is one of the pathways to the circular economy. Types of IS include energy cascade, fuel replacement and bioenergy production. In energy cascading, waste heat or steam, produced by one actor is reused by the other. IS can also occur when use of waste-derived fuels replaces conventional fuels and when organic waste is converted for use as bioenergy. (Fraccascia et al., 2021)

The circular bioeconomy improves resilience and optimises resource use via organic waste use in energy production (Georgescu et al., 2025) (read more about the resilience of energy systems in Section 3 below). In the transport sector biofuels from waste materials, for example bioethanol from forestry and crop residue and agricultural waste, offer another circular solution (Di Blasio et al., 2022). Carbon capture and storage or utilisation (CCS/CCU) technologies are a potential circular solution to mitigate climate change impacts from consumption of fossil fuels (Arias et al., 2023) (read more about CCS and CCU in Section 5.5).

Recycling has a central role in the circular economy in terms of improving the economic resilience and mitigating the environmental impact by reducing the reliance on primary resources and implementing material flow optimisation in value chains (Georgescu et al., 2025). By 2050, the demand for critical minerals used in energy systems is expected to increase drastically, which has placed efficient value chains in battery manufacturing in a key position to create closed loops for lithium and other rare minerals (Di Blasio et al., 2022). Simultaneously, waste from renewable energy technologies is rising. For example, approximately 78 million tons of waste from solar panels alone is predicted, which will cause challenges if not managed properly (Arias et al., 2023). In the EU 570 Mt of wind turbine blade waste will be produced by 2030 (Diez-Cañamero & Mendoza, 2023). Wind turbine blades are particularly difficult to recycle because they are composed of a complex mix of materials, including glass or carbon reinforcement fibres, epoxy resins, and polyesters, as well as copper wiring, steel bolts, and core materials such as wood or foam, often coated with polyethylene or polyurethane. As a result, this waste stream is still largely sent to landfill (Diez-Cañamero & Mendoza, 2023). Therefore, the recyclability of wind turbine waste, instead of incineration, landfilling and repurposing, is crucial (Diez-Cañamero &

Mendoza, 2023). Although waste amounts from solar PVs are modest compared to other types of waste, for example oil sludge and coal ash (Mirletz et al., 2023), improving the recyclability of renewable energy technology is needed.

A circularity approach in the design and planning (e.g. eco-design), is needed to improve the recycling and repairability of energy systems at the end-of-life stages to increase technology efficiency, to reduce the demand for critical minerals, and to ensure local supply (Arias et al., 2023). Therefore, the implementation of circularity standards in energy system design is needed. The more the energy sector relies on domestic cross-industry circular value chains, the more resilient and less vulnerable to geopolitics it becomes (Kumar et al., 2023). The energy transition will have positive and beneficial impacts only with sustainability and circularity compliance (Arias et al.2023).

3. A RESILIENT ENERGY SYSTEM—THE FOUNDATION OF OVERALL SECURITY

Authors: Jukka Lassila, Behnam Ivatloo, Pertti Kauranen, Jarmo Partanen, Esa Vakkilainen and Christian Breyer

Society's stability and ability to function depend on an energy system that functions reliably also in unexpected situations. A well-functioning energy system ensures secure access to electricity, heat, fuels, and other raw materials, and enables their distribution and use across different parts of society. How well energy systems operate has a direct impact on many critical basic functions, such as healthcare, water services, communications, food supply, security, and logistics, as well as the services that support them. This makes the overall management of the whole system increasingly important, especially as society becomes more and more dependent on electricity.

The development of electricity markets under EU regulations has been a key driver in renewing Finland's power system. Carbon dioxide emissions have fallen by 80%, security of supply has improved, and prices have remained among the lowest in Europe. In recent years, however, energy systems have undergone major changes that affect resilience, and therefore the functioning of society as a whole. These changes include a growing dependence of electricity generation on the weather and a move away from traditional fuels, a more geographically distributed generation mix, increasing electricity dependence in heat production, wider use of underground cabling instead of overhead lines, and rapid growth in distributed battery storage. These developments—both those already in place and those still evolving—have both positive and negative effects on reliability and resilience in the energy and power system.

Different energy sources, the forms of energy they provide, and how we use them all have critical roles for the functioning and competitiveness of our society. When using energy sources, three key boundary conditions stand out. First, supplying energy must not cause greenhouse gas emissions. Second, it must be economically viable and internationally competitive. Third, it should involve as much self-sufficiency as possible. Even though full self-sufficiency is not possible in every respect—and current societal and energy system conditions still require some use of fossil fuels—dependence on them can be significantly reduced. This reduction must be done in a way that does not weaken the overall resilience of energy systems. Russia's war in Ukraine and the crisis in the Middle East have increased the importance of all these goals.

3.1 Drivers and enablers

3.1.1 Distributed generation and weather dependence

Electricity demand is increasing rapidly as Finland advances towards a fossil-free energy system and strengthens its global industrial competitiveness. Electricity is produced across Finland in many different types of power plants. The Nordic countries form an integrated power system, where each country aims to follow

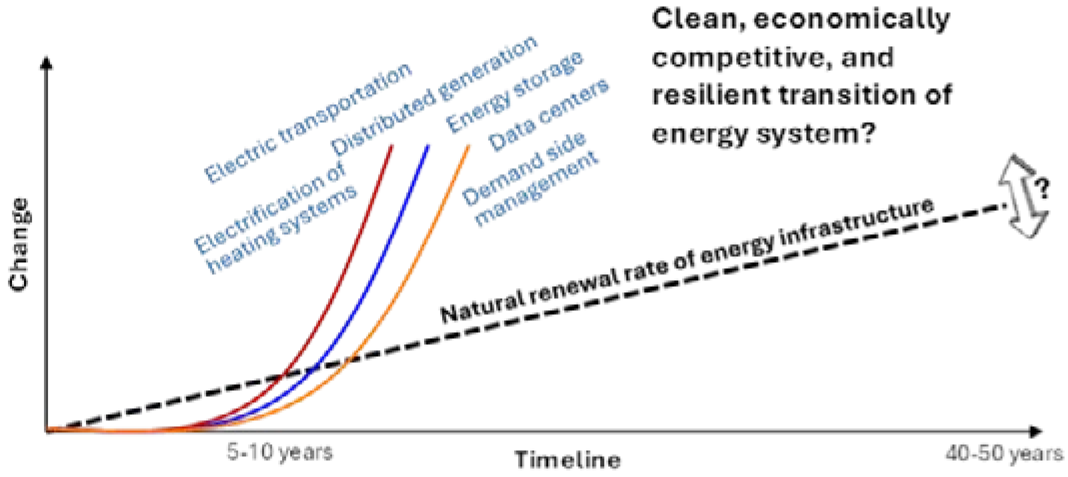


Figure 3.1. Scheduling challenge: development trends in the energy system and the natural renewal pace of energy infrastructure.

pre-agreed balances between generation and consumption. Some plants can change output very quickly, within seconds, while others need tens of minutes to adjust. For the power system to work, it is critical that generation and consumption remain in balance on a second-by-second basis. Because electricity can only be stored "as electricity" in relatively small amounts compared to total use, generation in practice must follow demand in real time. In the future, flexible load (for example flexible industrial demand, electric heating, and electric vehicle charging) should increasingly help maintain power balance actively.

The rapid growth of wind and solar power has reduced carbon dioxide emissions but also led to larger swings in electricity prices. Distributing generation by unit size and location has reduced the impact that any single plant or grid section can have on the reliability of the whole power system. Growth in domestic electricity production has reduced dependence on international connections and fuel stocks from the traditional security-of-supply perspective. At the same time, weather dependence and uncertainty in production have increased concerns about ensuring enough energy—especially during windless and cold periods—and about maintaining the power balance in all conditions.

3.1.2 Sector integration in the energy sector

Electrification is changing society in many ways, and dependence on electricity is growing especially through sector integration. For large energy volumes, solutions are being sought through energy conversion pathways such as the Hydrogen Economy and more recently the Power-to-X Economy (Breyer et al., 2024) (for example electrolysis and hydrogen storage) (see more on hydrogen solutions in Section 7.2.1). Hydrogen separated from water using electricity can become a key raw material and energy carrier in the coming decades, for producing different domestic synthetic fuels. Separating hydrogen from water requires a very large amount of electricity. At industrial scale, producing synthetic fuels would increase Finland's electricity use. Bio-based carbon dioxide can be used in synthetic fuel production, for example by capturing it from flue gases produced by many wood-processing industrial plants. If needed, our available raw materials are sufficient to shift Finland from an importer of fossil fuels to an exporter of fuels.

As heating and transport based on fossil energy sources are phased out, they will be replaced by electric boilers, heat pumps, and electric mobility. This increases the dependence of buildings and transport on electricity. This trend means that different parts of society—such as housing, work, mobility, and logistics—are increasingly tied to how well power systems operate. The importance of electricity will continue to grow, and uninterrupted access to it will become an even more central part of society's resilience.

Flexibility is regarded as a key characteristic in future 100% renewable energy systems due to the inherent variability of renewable energy sources. Based on a broad literature review on 100% RE systems, five distinct types of flexibility were identified: 1) different forms of energy storage, 2) demand response, 3) PtoX solutions, 4) longer distance transmission and distribution grids, and 5) curtailment of producing variable renewable electricity (Khalili et al., 2025). These flexibility forms also play together (Khalili et al., 2025): the variable supply of renewable electricity can be balanced spatially with transmission and distribution grids, balanced temporarily with storage, absorbed with demand response, distributed across energy sectors and into other energy carriers with power-to-X technologies, and curtailed as part of least cost energy systems. In addition, the supply complementarity of different sources of energy, such as wind energy, solar energy, hydropower, and bioenergy can considerably reduce the overall variability of the energy mix. The effective combination of flexibility options forms the basis for a stable and competitive energy system.

The diverse energy supply in the Nordics is a core basis for a stable and low-cost energy supply. The Nordic countries share distinctive characteristics in their energy systems, including significant hydropower resources with large dispatchable reservoir capacities, as well as substantial wind power, solar PV, and bioenergy availability. The complementarity of the different major sources of energy allows a stable and low-cost supply of energy for power demand, heat, and road transport. Finland also benefits from a stable baseload provided by nuclear power, along with diverse domestic energy resources, and it further draws on Nordic hydropower through strong electricity grid interconnections with its neighbouring countries. The benefits of sector coupling and power-to-X technologies can be regarded as considerable for Finland (Satymov et al., 2025).

3.1.3 Flexible load and technology development

The speed of the energy transition, combined with the slow renewal of the energy infrastructure, creates a mismatch that is being addressed by adding flexibility at different levels of the system. Changes in heating and mobility solutions, together with falling technology costs, make it possible to increase flexibility as a tool for managing both the energy and power balance. In developing energy infrastructure and ensuring reliability, distributed flexibility—and ways to manage it—are essential. However, if many distributed resources respond to electricity market signals at the same time (such as demand response solutions and battery storage), this can change the grid loading behaviour in an uncontrolled way, potentially putting reliability at risk and using capacity inefficiently. In this sense, adding flexibility can also introduce new challenges. In addition, power electronics and software solutions connected to distributed resources can create risks if an external party gains control of them, endangering overall security.

The need for flexible demand becomes especially visible as the number of data centres grows rapidly. Significant data centre capacity is being planned for Finland, and the scale of connection inquiries is exceptional from the perspective of the energy system. A key risk is that data centres typically have a nearly constant load and only limited flexibility. Computing capacity is needed based on customer demand, so consumption cannot be substantially shifted to match variations in renewable electricity generation (wind and solar). This can increase price spikes, tighten the power balance in extreme situations, and add pressure to grid investments. Despite these challenges, data centres can also act as an energy system resource if their UPS batteries and power electronics can provide short-term frequency and voltage support when needed. Backup generators can be used to support the grid during disturbances, as long as fuel logistics and permitting conditions allow longer operation if required. The overall impact of data centres also depends on their geographic location, for example in relation to regional generation potential and the use of waste heat. Risks related to the data centres can be reduced through proactive guidance, requirements, and financial incentives.

3.1.4 Regulation that supports progress

Developing the energy system has traditionally required a long-term approach, but the fast-moving energy transition challenges the traditional, gradual principles of infrastructure development. For the transmission infrastructure, there is concern about whether the regulations that oversee and guide monopoly operations can respond quickly enough in a changing world. At the same time, supervision should ensure long-term development of the transmission network and a stable investment environment, and encourage agile and new operating models that enable a resilient energy transition.

3.2 Goals and requirements for a resilient energy system

Energy systems must support a good quality of life and the development of society's functions fairly across all of Finland. The functional and organisational goals for resilient energy systems (technology, organisations, and legislation) can be summarised as a whole that combines equality, self-sufficiency, climate targets, and the ability to withstand disruptions. To reduce the dependency on external supply chains and the impact of geopolitical risks, systems should rely as widely as possible on domestic energy sources, components, and expertise. Energy systems also play a vital role in mitigating and managing climate change. Developing electricity and heat systems enables emission reductions and the shift to clean production. Significant added value can be created for society by using Finland's strong potential for clean electricity generation and by capturing carbon dioxide streams from bio-based industrial processes. Combining these elements makes it possible to produce carbon-neutral fuels and other products beyond domestic needs. However, this requires the ability to produce affordable electricity even in exceptional societal situations.

The technical systems that support reliability must be able to respond flexibly, efficiently, and partly automatically to both internal disturbances (such as widespread distribution outages) and externally caused technical and operational disruptions (such as damaging mains transformers, disabling personnel, or cyberattacks). When needed, the power system must be able to be quickly transformed—according to pre-plans—into several independent regional power systems, or even thousands of simultaneously operating "islands." The rapid spread of local generation and battery storage, combined with advanced IT and automation, make this possible without major additional costs. Several technically proven solutions are already in use, and at the smallest scale an independent power system can be formed at the level of a single household (including battery or storage and own energy production such as solar PV and heat pumps).

To ensure society's resilience, energy systems must work seamlessly together with national security systems. The energy infrastructure must not hinder the operation of related systems. For example, coordinating wind power construction with defence systems requires solutions that safeguard surveillance and radar operations while also enabling more wind power to be built. One example of ongoing work is the planned cooperation between the Defence Forces and wind power projects in Eastern Finland, where the use of wind turbine towers as support stations for the Defence Forces' radar system is being examined.

4. PEOPLE AND MARKETS

Authors: Salla Annala, Samuli Honkapuro, Juha Haakana, Minna Havukainen, Elena Poli, Ayesha Sadiqa and Eeva-Lotta Apajalahti

4.1 Functioning markets sustain energy security

Well-functioning electricity markets are a cornerstone for securing energy systems, as well as the availability, and affordability of electricity. Electricity markets consist of several layers of markets, which operate for different purposes and on different time scales. Furthermore, there are a large number of energy market actors who operate in these different layers. This section presents the basic market mechanisms and provides information on price formation in the electricity markets, including the recent discussion on setting a power-based price element to reduce energy consumption spikes for small-scale customers. The previous Energy Outlook presented a highly detailed description of how consumer energy prices are formed, and therefore, this is not included in the current Energy Outlook (see LUT Energy Outlook, 2024).

4.1.1 Several marketplaces

Most of the electricity is traded in *wholesale electricity markets* in Europe, which are based on marginal pricing principles. This means that the price for electricity is determined by the costliest production format. Figure 4.1 shows that supply side bids are put in ascending price order, and when the level of demand is met, the price is fixed to that level. Intersection of supply and demand curves is the marginal price, which is the same for all the sellers and buyers. Although there has been criticism for this pricing system, as it may lead to high price volatility and windfall profits of low-cost generation, no feasible alternative market design options have been found.

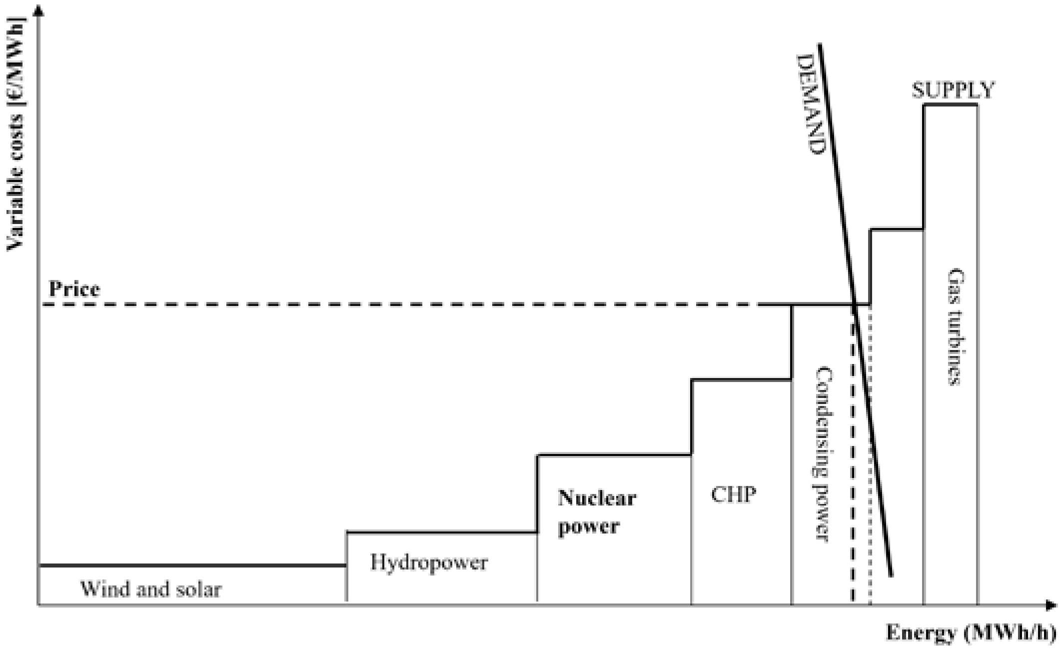
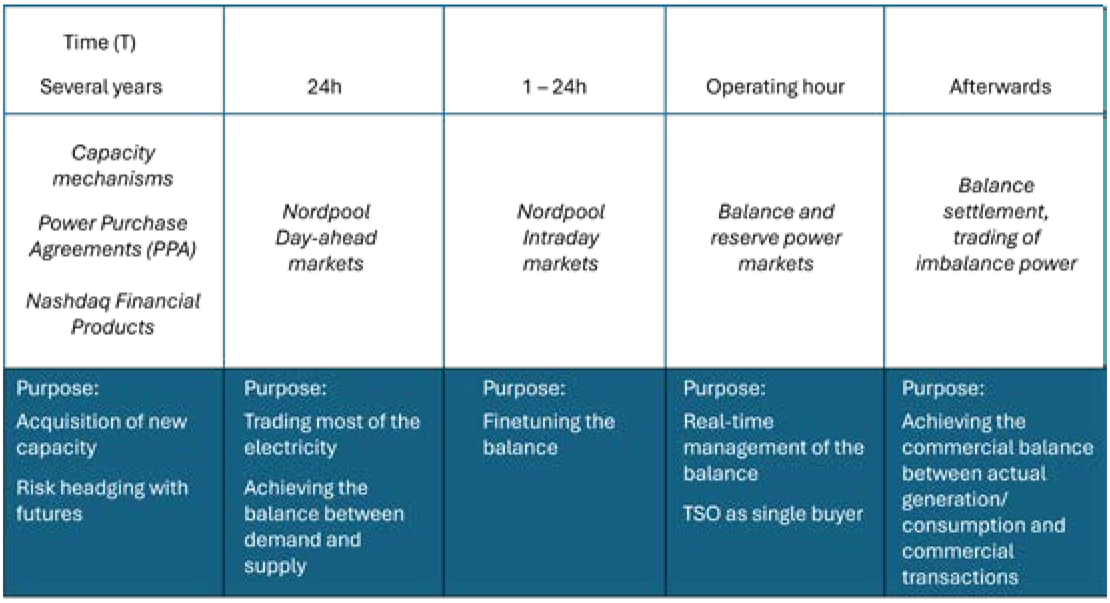


Figure 4.1. Marginal pricing of electricity in the wholesale electricity markets

In practice, all the sellers and buyers place their bids in a day-ahead market for every 15 minutes timeslots for the next day. After all bids are placed, and the availability cross-border transmission capacities is clear, the Euphemia algorithm calculates the prices by maximising both producer and consumer surplus. A consumer surplus is achieved when the marginal price is lower than the demand side is willing to pay, and a producer surplus exists when the marginal price is higher than the bidding price (i.e. the willingness of the supply side to sell electricity). The maximisation of the sum of surpluses leads to the maximisation of the total benefits. In addition to that, it also optimises cross-border trading, so that it leads to optimal results for the whole of Europe.

Marginal pricing promotes the resilience and power balance of the energy system. When there is scarcity of generation (e.g. when weather-based generation is not fully available), the price increases, because of the more costly energy production (gas in Figure 4.1) is required more. This in turn provides an incentive to decrease consumption. This ensures maintaining the balance between generation and loads, which, again, is vital for the power system. Therefore, during peak prices, demand decreases. This is how the market mechanism adjusts to the availability of energy with the demand for electricity. Furthermore, using supply-side bids ranked in descending price order ensures that the lowest-cost generation mix is dispatched at any given moment, including sources such as solar, wind, hydro, and nuclear (Figure 4.1). Prices also convey information about the electricity markets; high prices give investment signals for new generation, whereas low prices promote investments of the energy intensive industries.

In addition to the above-described day-ahead market, there are *short-term intraday and reserve (intra-hour) markets*, to promote short term balancing and frequency regulation capacity. Furthermore, there are *financial markets to trade derivatives* that traders in electricity markets use for risk hedging. In addition to these marketplaces, large-scale users and producers of electricity can make bilateral long-term purchase contracts, such as *Power Purchase Agreements* (PPAs). Figure 4.2. below shows the different markets, the time-scale of the trading, and the purpose of the markets.



Time (T) Several years	24h	1 – 24h	Operating hour	Afterwards
Capacity mechanisms *Power Purchase Agreements (PPA)* *Nashdaq Financial Products*	*Nordpool Day-ahead markets*	*Nordpool Intraday markets*	*Balance and reserve power markets*	*Balance settlement, trading of imbalance power*
Purpose: Acquisition of new capacity Risk headging with futures	Purpose: Trading most of the electricity Achieving the balance between demand and supply	Purpose: Finetuning the balance	Purpose: Real-time management of the balance TSO as single buyer	Purpose: Achieving the commercial balance between actual generation/ consumption and commercial transactions

Figure 4.2. Different electricity markets, timescales and their purpose

Power Purchase Agreements (PPAs) were first introduced in Finland in 2018 along with first contract made for wind power production (Renewables Finland, 2019). PPAs are a contract typically between a renewable energy producer and a large-scale industrial energy user, such as a datacentre. However, PPAs can be also made between CO_2 providers and users, or any other type of a product, which do not necessarily have an established marketplace. A PPA contract is typically a long-term contract, spanning from 10 to 20 years, during which the price of electricity is fixed. PPAs have played an important role in renewable energy projects. They increase the security of energy price for both parties, and improve the bankability of renewable energy projects, as the agreement secures the buyer for the electricity. PPA contracts are bilateral between seller and buyer, and details vary between the contracts.

4.1.2 Markets are being developed constantly

Although the present market design has proven to be well-functioning, the transition towards variable renewable energy dominated systems raises the need for additional market elements. To secure adequate capacity during the long cold and calm winter periods, but also during the long-term failure of a large generation unit or transmission line, a remuneration mechanism for such back-up capacity investments is needed. The regular market mechanisms—which are based on scarcity prices, and which give signals for new investments in the private sector—do not apply here, because the above-described occasions are too rare. This mechanism could consist of an auction for investment support for such rarely operated power plants, which would most likely be gas turbines or motors which could be fuelled by bio or synthetic fuels.

Under normal conditions, such scarcity events, —when back-up power would be required— typically occur only once a decade. However, if there is a failure in a major power plant or transmission line, such a situation might occur much more often. Based on modelling results (Salmi & Honkapuro, 2025), the value of the lost load under such situations is lower than the cost of maintaining a reserve capacity. Hence, from a purely economic viewpoint, lower societal costs would occur by allowing a loss of load during rare scarcity events. However, prioritising supply security might be more important than achieving the lowest possible costs. After all, the additional overall costs for the electricity users for the reserve capacity are minor (less than 0.3 c/kWh).

It should also be noted that wind power availability is generally better during the winter than in summer, and hence, it correlates with power demand seasons. For instance, the all-time highest power demand in Finland was on 8th of January 2026, when the highest power demand (at a 15 min resolution) was 15,279 MW. At the same time, wind power generation was over 5,000 MW.

The description above concerns the wholesale market, where generating companies sell electricity, and large-scale customers and retailers purchase electricity. Electricity retailers furthermore sell the electricity they have purchased to their customers, including residential customers, and other sectors that do not have access to wholesale markets. All customers have the right to choose the electricity retailer, from which they purchase their electricity. Retail companies offer a range of contract types, typically divided into fixed-term and open-ended agreements, with pricing structures that may be either flat or dynamic (see more details on customer price formation in the previous Energy Outlook 2024).

4.1.3 Steering towards demand response and energy saving in peak hours

There are significant, ongoing structural changes in electricity end-use sectors. Developments such as electric mobility, the electrification of heating, electrical energy storage, and market-based demand response are reshaping energy demand patterns and grid loads. At the same time, on the production side, the increasing share of variable renewable energy is introducing greater volatility into electricity prices across energy systems. Challenges are emerging especially during energy consumption peaks, which we have witnessed recently, for example, on very windy days when the prices have been very low.

If customers lack incentives for peak-cutting, this can lead to substantially higher peak loads, increasing the need for investment in distribution grids, and ultimately raising costs for end users. Electricity contract models provide different means to incentivise end-users to reduce their energy consumption during peak hours.

The primary and most effective mechanism is the pricing of electricity (fee structure in retail contracts). Under dynamic pricing contracts, electricity prices faced by customers directly reflect market prices, enabling end-users to achieve cost savings by shifting their consumption from high-price periods to lower-price periods. This is called demand response. Demand response supports the power balance of the system, as it decreases the loads during the events of generation scarcity. However, dynamic pricing contracts contain a risk of high price spikes. Hence, although the average price in long-term is typically lower in dynamic pricing than in flat tariff contracts, choosing dynamic pricing requires that the energy end-user has a financial buffer against price spikes. For this reason, many customers choose a flat tariff instead of dynamic pricing, where the price of electricity remains mostly the same for the whole contract period.

Offering flexibility to reduce peak consumption is becoming increasingly important in future energy systems. Customers, so-called flexumers, may offer flexibility to the power system by 1) adjusting their consumption based on variations in electricity prices as described above, or 2) allowing external control of their major loads, for example offering services to the Transmission System Operator (TSO). Currently, about a third of Finnish electricity retail customers have a dynamic price contract in which the price varies based on the variations in the wholesale market price. In September 2025 the wholesale electricity market transitioned from hourly to quarter hourly pricing. As a result, retail customers on dynamic tariffs have also moved to quarter-hourly pricing, if supported by their metering infrastructure.

Previous research has shown that energy customers react at least to extreme price events, although the research highlights that not all customers on spot prices can be flexible (e.g. Haakana et al., 2025). While increasing granularity in pricing encourages adaptation to the situation in the power system, it also adds to the complexity in customer decision making and emphasises the importance of technological solutions to control electric loads. However, the costs of such control systems may act as an investment barrier.

The second aspect involves network fees, which are collected by distribution system operators (DSO), who have a regional natural monopoly position. DSOs and network fees are heavily regulated by the Energy Authority, who has set a revenue cap for the DSOs. DSOs can choose their pricing parameters, but the revenue (pricing as whole) has to be within limits set by the Energy Authority. The network fee for a small-scale customer usually consists of a fixed stand-by fee (€/month) and an energy fee for the transmitted energy (c/kWh), which depends on how much electricity the customer uses. However, the costs of the network are fixed in the short-term, and in the long-term they depend on the peak power of the network. Because of this, energy fees are not cost reflective, and to cover network costs DSOs have been increasing fixed fees and reducing energy fees. For these reasons, network fees do not adequately guide energy consumption, and their potential to impact peak energy consumption is very low.

To address the limitation that network tariffs do not effectively steer consumption during peak periods, distribution system operators (DSOs) are introducing power-based components (€/kW) into network fees for small-scale customers. For larger customers, a power-based fee has been in use for a long time. This does not increase the DSOs' revenues, as it is limited by the Energy Authority, nor does it increase overall network fees, rather, it adjusts the relative proportions of their components. Introducing a new power-based element to the network pricing, the proportional share of the fixed and energy fee decreases. This means that small-scale energy users, who use a lot of electricity (electric heating, EVs) would pay higher network fees as they use the most power. This would incentivise reducing peak electricity consumption. Additionally, the move towards more cost-reflective pricing promotes a fairer allocation of network costs among customers.

The Energy Authority (2026) has issued a decree specifying how the price components of the network fee should be formed. It states that the power-based price component must be calculated based on the highest hourly power demand within a month (€/kW, month). However, each DSO is free to choose absolute prices and whether they would like to introduce a power-based element for small-scale customers or not. The Energy Authority's decree aims to ensure that all DSOs adopt a harmonised approach, enabling consistent implementation across the sector. This, for example, facilitates the deployment of energy automation devices and related services nationwide in Finland under uniform principles.

4.2 Active energy citizenship and energy communities

4.2.1 Active energy citizens

Electricity markets form the foundation of electricity pricing, while retailers offer electricity contracts to end customers. Traditionally, the role of customers (energy end-users, citizens) has been to choose and purchase the contract model and consume the purchased energy. However, all customers can also take more active roles in the energy system.

Energy communities, energy citizens, energy prosumers and those who offer energy flexibility, so-called flexumers, are expected to promote a more active role for households and individual people in our energy systems. Customers can become prosumers, which means that they can produce their own energy, at least partially. For example, by installing micro-generation, solar PVs and heat pumps, and selling any surplus energy to grid. By producing their own energy, households can benefit by not paying high electricity prices in case of strong price fluctuations (and when they do not have a flat pricing contract) and by receiving extra income from electricity when selling surplus energy to the grid. Furthermore, customers within the same property, for example in one apartment building, can form an energy community and share locally generated electricity within the community. This section presents the main drivers and forms of active energy citizenship and energy communities.

The main drivers for more active energy citizenship come from the EU vision that citizens should play a central role in the ongoing energy transition. The concept of energy citizenship recognises citizens as active participants in the energy system instead of passive consumers (Public Participation, Art 6 of Directive 2001/42). Citizens can take on various dynamic roles within the energy sector, which can intersect and evolve over time. Active citizenship is connected, in addition to prosumerism, in promoting the decentralisation of energy systems, its potential to contribute to alleviating energy poverty, and mitigating environmental anxiety (Biresselioglu, 2024).

In principle, energy citizenship refers to perceived empowerment to make decisions about energy use and production. Increasingly, citizens are being invited to engage in the planning and development of new energy infrastructure, though often under specific conditions (Lennon & al, 2019). Furthermore, energy citizens can become co-investors in energy initiatives, and governors of local energy systems. This means that energy citizenship becomes essential for achieving climate goals, rather than being just another form of civic or political “citizenship” (Devine-Wright, 2012). To enable more active energy citizenship, many of the decision-making processes in the energy sector require more inclusive, participatory approaches. Active energy citizenship also changes the traditional business models in the energy sector.

4.2.2 Energy communities

Community energy initiatives enable people to jointly produce, store, and trade renewable energy, bringing environmental, economic, and social gains directly to households and neighbourhoods (Wittmayer et al., 2021). Research shows that such initiatives mobilise local tacit knowledge, strengthen civic empowerment, and improve regional socio-economic development, especially when communities or households own the energy solutions (Dall-Orsoletta et al., 2022). Energy communities are expected to create the following benefits: increased transparency in decision-making, a better democratised energy system as well as more equal distribution of profits, increased social acceptance of renewable energy, and community empowerment by creating jobs and increasing resilience (Van Bommel and Höffken, 2021).

Energy communities have roots in the citizen-led wind and solar initiatives that emerged in Germany and Denmark after the 1970s oil crisis (Gorroño-Albizu et al., 2019). Nowadays, they take many forms, enabling collaboration between residents, municipalities, and small businesses to generate, exchange, store, and consume low-carbon energy. The EU is promoting the participation of energy communities in renewable energy in its revised Renewable Energy Directives, RED II (EU, 2018/2001) and RED III (EU, 2023/2413), and the Electricity Market Directive (IEMD). These allow consumers to participate directly in energy markets, supply, and demand-response (EU, 2019/944). The EU has included two types of energy communities in the legislation: citizen energy communities, which refers to a group that can be established by members or shareholders to initiate a renewable energy project, and renewable energy communities, where there is a requirement for shareholders or members to live in the proximity of the renewable energy installations (EU, 2018/2001).

The EU sees energy communities as a way to increase the renewable energy capacity and public acceptance, mobilise private capital, provide flexibility to the electricity system, and empower consumers (Vernay et al., 2023). Beyond technology, energy communities are social and organisational innovations: they reshape both infrastructures and sociopolitical relationships in the energy sector as countries shift from centralised fossil systems to more dispersed energy systems based on renewables (Walker and Devine-Wright, 2008). They are also broadly expected to deliver a wide range of social benefits: democratising energy governance through enhanced citizen participation and improved transparency in decision-making, strengthening local resilience and social capital, lowering energy costs and reducing energy poverty, fostering local empowerment through skills and confidence building, and distributing benefits from the energy transition more fairly (Ruggiero et al., 2026).

The number of energy communities and citizens varies in Europe. Schwanitz et al. (2023) estimated that there are approximately 10,500 citizen-led energy initiatives operating in Europe with 7-10 GW of installed renewable capacity in 30 countries, reaching over 2 million citizens. Despite the attention focused on energy communities, the hopes placed upon them, and the potential (27% of EU final energy consumption is by households), energy communities represent only a modest share of Europe's energy mix. Although national and EU legislation support the formation of energy communities, their development in Finland has been limited. Currently, there are 376 registered citizen-led energy communities, out of which only 19 are located in the North and East Finland (Sorsa, 2025).

Despite their potential, energy communities face significant social and organisational challenges. Internal inequalities and power dynamics can create tensions, when, for example, financial benefits are captured by a small group of residents, undermining trust and acceptance within communities (Walker et al., 2010). Additionally, participation in energy communities remains skewed toward highly educated, older white men, leaving vulnerable groups underrepresented. Ensuring fairness also requires continuous negotiation between technical developers and citizens to reconcile diverse values and expectations (Mihailova et al., 2022). Moreover, positive social outcomes such as cohesion, resilience, and empowerment depend heavily on existing social bonds and local traditions of citizen involvement, and in some cases, communities may even experience disempowerment (Ruggiero et al., 2026).

Although the environmental goals of cities support the formation of energy communities, the decision-making and planning structures, material requirements and other construction sites in cities can create challenges and tensions regarding the formation of energy communities (Apajalahti & Matschoss 2021; Apajalahti et al., 2023). Therefore, support for the formation of energy communities requires collective action not only from citizens coming together, but also in terms of city planning, regional energy companies and grid owners, legislative changes.

4.3 Societal resilience and energy vulnerability

4.3.1 Societal resilience

Energy communities and active energy citizenship can improve the societal resilience of regions, and thus contribute to securing contemporary energy systems. In the context of energy, societal resilience encompasses the capacity of communities and institutions to adapt to energy disruptions, while maintaining trust, legitimacy, and social cohesion. Societal resilience encompasses how public acceptance, participation, and local engagement collectively shape the stability and adaptability of energy systems. Furthermore, energy communities and active energy citizenship can reduce the harmful impacts of grid disruptions and give access to energy during black outs. However, energy communities in Finland rarely operate off-grid, as their technical design typically maintains a connection to the main grid.

Community participation has proven to be especially important in renewable energy development. Active involvement of communities ensures that decisions reflect local needs and priorities, fostering a sense of ownership, responsibility and inclusion. For example, in the wind power sector, societal resilience is enhanced when communities experience ownership, influence, and tangible benefits from local projects. The most notable example of this are decentralised and cooperative ownership structures in Denmark, where policies that enabled community co-ownership anchored wind power development within local institutions, and fostered a sense of responsibility and acceptance (Vasstrøm et al., 2024). These initiatives have distributed economic benefits, widely strengthening societal resilience (Mendonça et al., 2018).

Northern Europe's energy systems are increasingly shaped by diverse ownership models, ranging from centralised state and municipal-led energy companies to decentralised, community-led initiatives. These models have significant implications for energy resilience and justice, affecting who controls energy resources, how benefits are shared, and how systems respond to disruptions. Therefore, the ownership models demonstrate how control over energy resources shapes not only technical robustness but also societal preparedness and perceptions of fairness. It is also important to acknowledge that societal resilience is not static. It is continually shaped through dialogue, contestation, and ongoing reconfiguration of policy frameworks, ensuring that decision-making processes remain responsive to community needs.

4.3.2 Energy vulnerability

Becoming active energy citizens—through self-generation of energy or participation in energy communities—requires awareness, skills, and a sense of responsibility, as well as access to opportunities and sufficient economic and social capital. However, a large share of the population does not have these. Already the high energy prices following Russia's invasion of Ukraine and the ongoing war in Iran, along with continued volatility in electricity prices, have exposed energy-vulnerable groups and pushed many households—previously not considered vulnerable—towards energy poverty (generally considered if >10% of household income is spent on energy). To cope with rising costs, many households have reduced energy consumption and cut other essential expenses, such as food, leading to financial stress and anxiety, even in Finland.

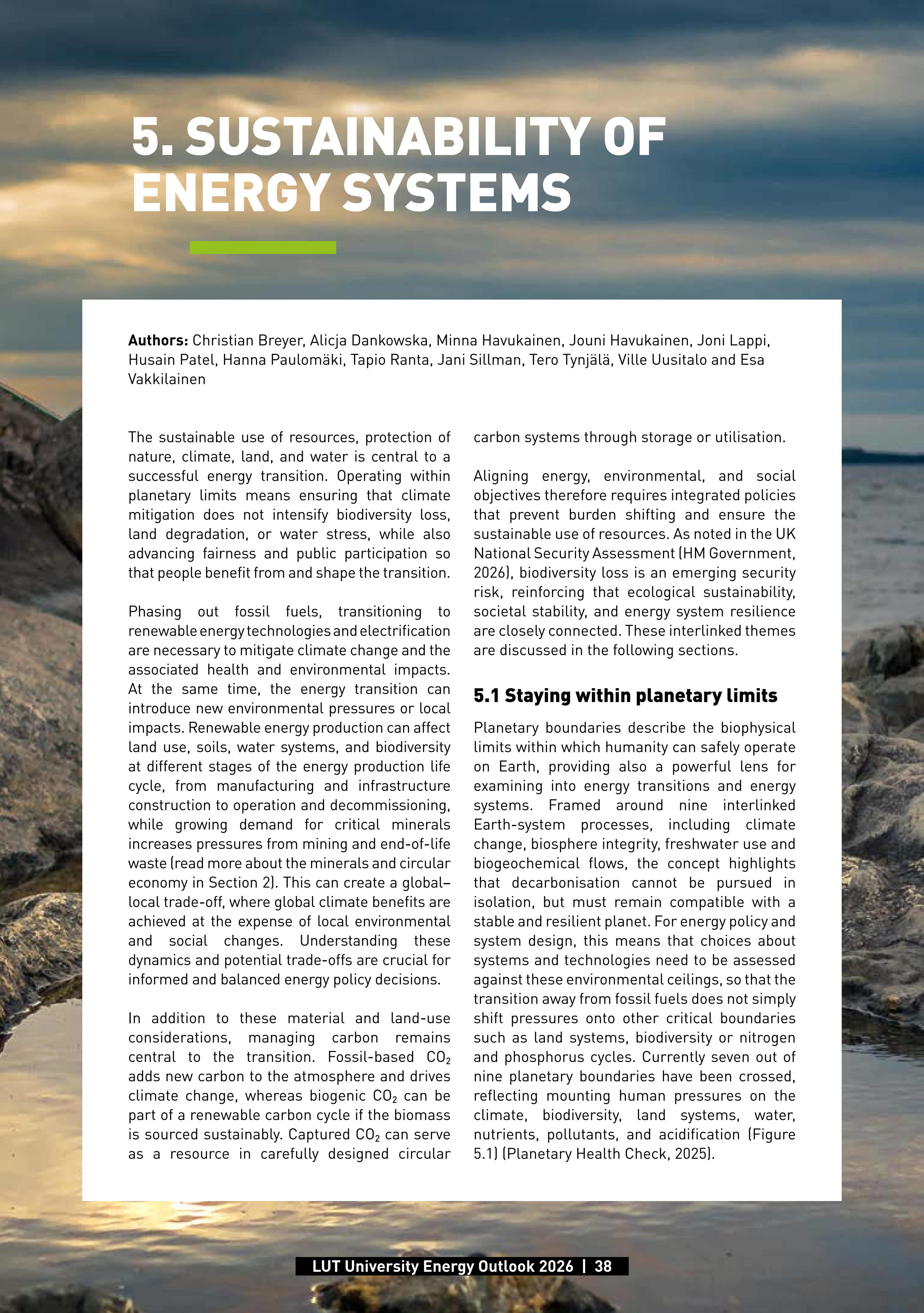
Vulnerable groups who already struggle to cope with their monthly energy bills are less likely to invest in their own energy production, flexibility or smart home automation solutions, which can be used to reduce the amount of energy purchased. Therefore, incentives to form energy communities or to generate self-produced energy should be carefully considered. Otherwise, these can reproduce or create more inequalities, if wealthier households gain disproportionate access to technologies such as microgrids or energy storage systems, thereby widening socio-economic divides. Higher-income groups often benefit more from incentives associated with low-carbon transitions, raising distributional justice concerns (Sovacool et al., 2019).

A range of factors—individually and in combination—contribute to energy vulnerability, including age, gender, disability, and family structure. Pensioners, disabled individuals, and women—particularly woman single parents—are identified as more vulnerable due to uneven income distribution and care responsibilities. Elderly individuals or families with small children also have elevated energy needs, making them more susceptible to energy vulnerability and poverty. Geographic and housing conditions play an additional role: rural areas, older housing stock, and certain heating methods can either exacerbate or mitigate vulnerability. (Numminen et al., 2024)

These cases underscore the need for policymaking that recognises differentiated vulnerabilities and incorporates them into resilience planning. Currently energy policies are too generic, focusing for example on energy efficiency improvements, increasing renewable energy and investment, while more tailored measures targeted for vulnerable groups are needed (Kajoskoski et al., 2025).

In Finland, energy vulnerability and energy poverty (Numminen et al., 2024), have received very little attention, although it has been acknowledged as an increasing problem especially due to high price spikes. An extensive research survey on Finnish households' energy poverty, conducted during the energy crisis in 2022, shows that 18% of households in detached and semi-detached houses exceeded the energy poverty limits (>10% income goes to energy bills) and 27% regularly felt the energy costs were a burden (Numminen et al., 2024). The general view is that Finland's welfare state and social benefits help vulnerable groups and alleviate poverty, but this is not the case with energy, as evidenced during the high energy prices in 2022.

Energy vulnerability can also increase in other ways in the energy transition. This may occur, for example, if local communities do not have access or the possibility to influence large-scale energy projects which affect their daily lives or livelihoods. Therefore, discussions on vulnerability in the energy transition are important, as this process would make inequalities visible and this in turn could help to design energy policies with justice implications. This increases energy justice, which combines distributive, procedural, and recognitional justice—and aim to address the central concerns of affordability of energy, equitable access to energy, and guaranteeing the fair distribution of both benefits and risks. Disparities emerge when households or communities face risks or costs without adequate compensation. An example of energy projects which might generate energy vulnerability or increase societal resilience are large-scale wind power developments and related infrastructure investments, such as roads and grids, which have prompted concerns regarding the uneven distribution of economic gains and environmental burdens. When local populations face landscape changes, noise, or other externalities without meaningful participation or if benefit-sharing mechanisms are lacking, their vulnerability increases and public acceptance is jeopardised (Apajalahti & Galvao Lyra, 2025).



5. SUSTAINABILITY OF ENERGY SYSTEMS

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The sustainable use of resources, protection of nature, climate, land, and water is central to a successful energy transition. Operating within planetary limits means ensuring that climate mitigation does not intensify biodiversity loss, land degradation, or water stress, while also advancing fairness and public participation so that people benefit from and shape the transition.

Phasing out fossil fuels, transitioning to renewable energy technologies and electrification are necessary to mitigate climate change and the associated health and environmental impacts. At the same time, the energy transition can introduce new environmental pressures or local impacts. Renewable energy production can affect land use, soils, water systems, and biodiversity at different stages of the energy production life cycle, from manufacturing and infrastructure construction to operation and decommissioning, while growing demand for critical minerals increases pressures from mining and end-of-life waste (read more about the minerals and circular economy in Section 2). This can create a global–local trade-off, where global climate benefits are achieved at the expense of local environmental and social changes. Understanding these dynamics and potential trade-offs are crucial for informed and balanced energy policy decisions.

In addition to these material and land-use considerations, managing carbon remains central to the transition. Fossil-based CO_2 adds new carbon to the atmosphere and drives climate change, whereas biogenic CO_2 can be part of a renewable carbon cycle if the biomass is sourced sustainably. Captured CO_2 can serve as a resource in carefully designed circular carbon systems through storage or utilisation.

Aligning energy, environmental, and social objectives therefore requires integrated policies that prevent burden shifting and ensure the sustainable use of resources. As noted in the UK National Security Assessment (HM Government, 2026), biodiversity loss is an emerging security risk, reinforcing that ecological sustainability, societal stability, and energy system resilience are closely connected. These interlinked themes are discussed in the following sections.

5.1 Staying within planetary limits

Planetary boundaries describe the biophysical limits within which humanity can safely operate on Earth, providing also a powerful lens for examining into energy transitions and energy systems. Framed around nine interlinked Earth-system processes, including climate change, biosphere integrity, freshwater use and biogeochemical flows, the concept highlights that decarbonisation cannot be pursued in isolation, but must remain compatible with a stable and resilient planet. For energy policy and system design, this means that choices about systems and technologies need to be assessed against these environmental ceilings, so that the transition away from fossil fuels does not simply shift pressures onto other critical boundaries such as land systems, biodiversity or nitrogen and phosphorus cycles. Currently seven out of nine planetary boundaries have been crossed, reflecting mounting human pressures on the climate, biodiversity, land systems, water, nutrients, pollutants, and acidification (Figure 5.1) (Planetary Health Check, 2025).

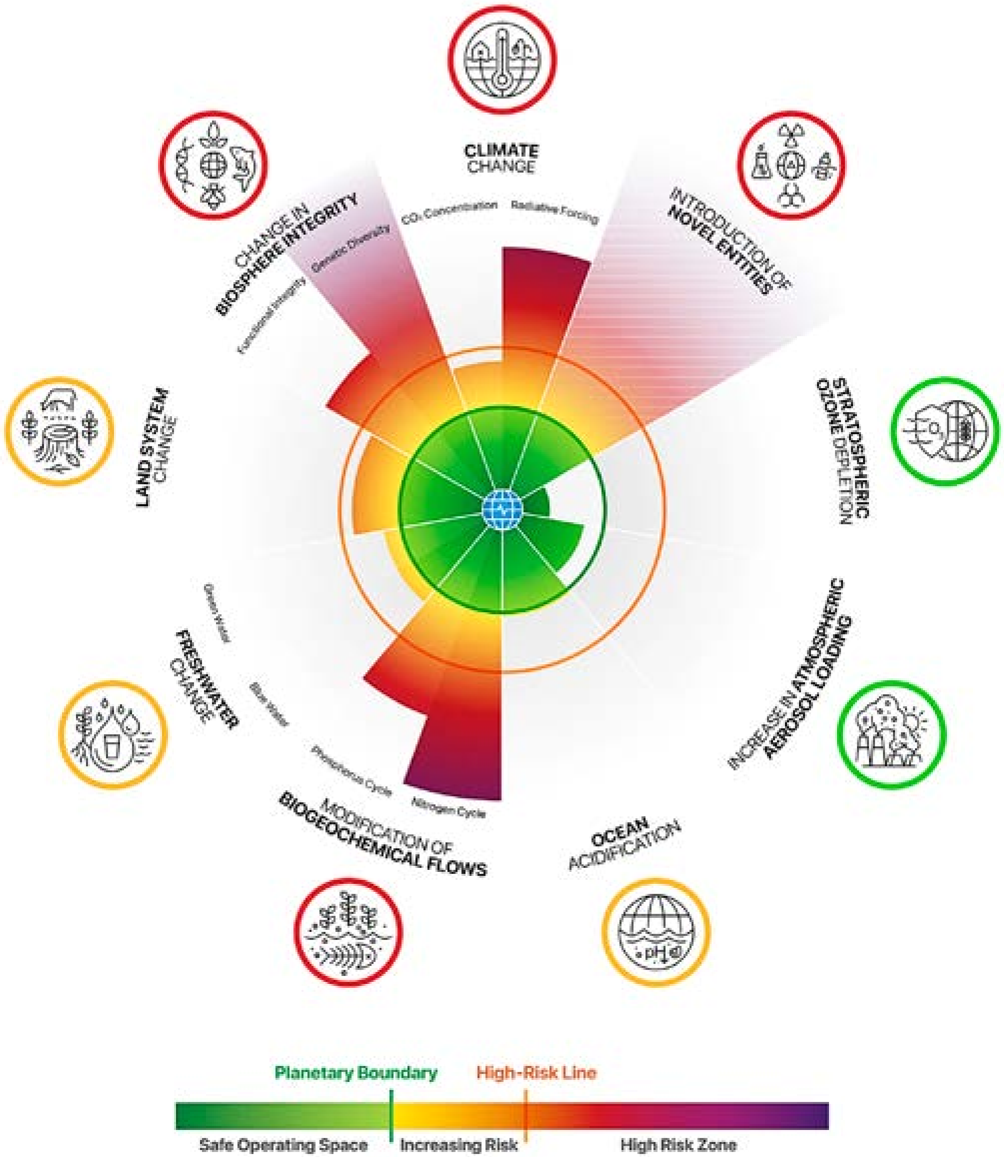


Figure 5.1. The Planetary Boundaries diagram presents the current state of nine Earth system processes that regulate planetary stability. Each boundary is quantified using one or more control variables based on observational data, model simulations, and expert assessments. The extent of each wedge represents the current status relative to the Safe Operating Space, with extensions beyond the boundary indicating transgression. Seven out of the nine boundaries have been exceeded. The dark green circle denotes the Planetary Boundary, and the thin orange line indicates the high-risk threshold (Planetary Health Check, 2025). This file is licensed under the Creative Commons Attribution 4.0 International license.

To remain within the planetary boundaries for climate change, it is useful to briefly review the key outcomes agreed at the recent UN Climate Change Conferences of the Parties (COPs). This provides a basis for assessing whether the established mitigation targets are being met and to what extent current actions align with agreed climate goals.

The Paris Agreement aims to keep the global temperature rise well below 2°C above pre-industrial levels, while striving to limit it to 1.5°C to reduce climate risks. The long-term vision was to achieve net-zero greenhouse gas emissions by the middle of the century, supported by regular progress reviews, transparency, and international cooperation to mobilise finance, technology, and capacity-building for sustainable development (COP21 2015). This commitment was reaffirmed at the COP30 in Belém (COP30, 2025), yet the member states fell short of agreeing on a global roadmap to phase out fossil fuels, despite strong support from many nations. The summit delivered major financial pledges. It also launched the Belém Mission to 1.5°C and a Just Transition Mechanism to ensure inclusive climate action. However, the lack of binding commitments on fossil fuel phase-out and deforestation was widely criticised.

Current climate mitigation efforts are insufficient to meet the Paris Agreement goals (Emission Gap report, 2025). If only existing policies are implemented, global temperatures are projected to rise by approximately 2.6–2.7°C by 2100, with some estimates reaching as high as 3.1°C. Full implementation of the current national pledges could reduce this to around 2.3–2.5°C, while an optimistic scenario assuming all announced net-zero targets are achieved might limit warming to about 1.9–2.1°C. However, these optimistic outcomes are considered unlikely under present trends.

Similar messages can be seen from the Climate Action Tracker (CAT) (Climate Action Tracker, 2009); an independent science-based project that evaluates national climate policies and pledges against the Paris Agreement goal of limiting warming to 1.5°C. CAT highlights that fossil fuel expansion continues to offset progress in renewable energy deployment, and that emissions are expected to peak by the end of this decade without the steep decline needed to meet climate goals. Stronger 2030 and 2035 targets and accelerated mitigation measures are essential to close the gap and avoid the worst impacts of climate change. Only two countries, Norway and United Kingdom, were on track to keep global warming below 1.5°C.

It seems evident that the mitigation actions are not enough to keep global warming below 2.0 or 1.5°C. This stresses the urgency of transitioning to a fossil-free energy sector as the energy sector remains the largest contributor to anthropogenic global warming, suggesting that demand for cleaner energy solutions should continue to expand. As global warming seems likely to exceed 2.0°C, it can be argued that the need to allocate sufficient economic resources for climate adaptation is increasingly evident. This is particularly true for those countries that have already mitigated most of their emissions or have historically contributed less to global greenhouse gas emissions but may face growing burdens of adaptation.

The challenge with the planetary boundary for climate change is even more severe, as the safe and just limit is closer to 1.0°C, rather than 1.5°C (Rockström et al., 2023). This threshold corresponds to atmospheric CO_2 levels of around 350 ppm, reflecting the climate of the late 1980s (Hansen et al., 2008). However, no scenarios assessed by the Intergovernmental Panel on Climate Change Sixth Assessment Report reach 1.0°C, and only a few pathways approach 1.0–1.2°C. These rely on problematic assumptions, such as excessive bioenergy use or economic contraction that could hinder efforts to reduce energy poverty in the Global South.

Recent studies suggest that reaching the 1.0°C boundary may still be feasible through large-scale renewable energy deployment and carbon dioxide removal (Breyer et al., 2023; Mühlbauer et al., 2025). Achieving this would require about 10% more primary energy and cost roughly 0.6% of global GDP. However, the economic benefits of limiting warming to 1.0°C instead of 1.5°C could increase the global GDP by around 8%

(Burke et al., 2015), far exceeding the additional costs.

At the same time biodiversity loss (biosphere integrity), another major crisis is causing increased uncertainty for humanity due to its severe consequences for life supporting ecosystem services (Richardson et al. 2023; WWF 2024). In 2022, the international Kunming–Montreal Global Biodiversity Framework was agreed to halt biodiversity loss by 2030 (GBF 2022). Currently, the main direct driver for biodiversity loss in terrestrial ecosystems is land use and its change, but as global warming intensifies, it might become the most important driver in the future (IPBES 2019) (see more on land use and biodiversity under Section 5.3). Biodiversity loss also contributes to growing greenhouse gas emissions, e.g. via deforestation and changes in ecosystem structures. For example, deforestation and climate change together may lead to a tipping point where the Amazonian rain forest becomes a carbon source instead of a sink, which would make achieving the 1.5 °C target impossible. (Nobre et al. 2021; WWF 2024, Järvinen et al. 2025). This highlights the importance of planning the energy transition so that it supports tackling both climate and biodiversity crisis simultaneously. The protection of land, nature, and water will be discussed in more detail below.

5.2 Social sustainability and justice in the energy transition

Together with environmental and economic dimensions, social factors form the cornerstones of just and sustainable energy transitions. Social acceptance ultimately determines the pace of the change.

Social acceptance builds upon public participation, trust, and ownership, and it has several dimensions (Wüstenhagen et al., 2007). It includes how people in general view the energy transition, how local communities respond to concrete projects and changes in their own surroundings, and how markets and investors react to new energy solutions and innovations. Social acceptance is also shaped by practical outcomes, such as job creation and local economic development, which influence how people experience and evaluate the energy transition in everyday life (Wüstenhagen et al., 2007). The energy transition happens at many different scales, from local communities to national and regional levels.

Local actors can drive the energy transition, but the impact is often limited by EU and national policies. This calls for coordinating policies on various scales as support for energy communities is most effective when tailored to their needs and backed by local policies and participation and adequate resources are guaranteed (Liljenfeldt, 2025). Understanding these factors can help design policies that enable communities to lead the shift towards sustainable energy.

When inclusion and community participation are lacking, decarbonisation efforts risk reinforcing existing social inequalities or failing altogether (Rehman et al., 2026). For this reason, active public participation is widely recognised as a cornerstone of successful energy projects and the energy transition more broadly, which is a priority also emphasised in the European Green Deal. There are high expectations on expanding the role of prosumers, citizens and communities that instead of being merely consumers of energy, become producers, investors and governors of local energy systems (see Section 4 on people and markets for more details on energy citizenship).

The energy transition can deliver important socio-economic benefits, such as stronger and more resilient economies, enhanced social equality and inclusion, better health, or more jobs (UN, 2021). But to achieve these benefits, what is required is the involvement of not only national governments and large companies, but also entrepreneurs, municipalities, and civil society—citizens and local organisations—working together to shape energy decisions and future energy systems.

The transition to distributed renewable energy systems with the active involvement of households can transform which social groups hold power in the energy sector. Widespread deployment of rooftop solar panels, community wind projects, local storage, and smart meters support citizens in terms of becoming more active participants in energy markets: instead of energy flowing only from big producers to passive consumers, people can become prosumers—generating, storing, and exchanging their own energy (Jimenez Iturriza et al., 2019)—and thus enable a broader shift toward decentralising and democratising energy systems.

Citizens who become prosumers undertake a much more responsible role, as they are no longer simply expected to pay bills on time, but they actively take part in how energy is made, managed, and shared. This matters because households use a large share of energy: in the EU, they account for 27% of the final energy consumption (Eurostat, 2022). That means that everyday choices play a big role in the transition, and citizens can support this process through different means—not only by becoming prosumers, but also saving energy, modifying their lifestyles (e.g. traveling less by air), shifting to electric transport, or insulating their houses.

Importantly, for the low-carbon transition to win broad support, it must be just. That means it should not reproduce or deepen existing inequalities, and it should work for all social groups, including the most vulnerable. As the President of the European Commission, Ursula von der Leyen, said in 2020: "People are at the core of the European Green Deal... And it will only work if it is just—and if it works for all. We will support our people and our regions that need to make bigger efforts... to make sure that we leave no one behind" (quoted in the EC, 2020). What is crucial here is that transitions are not just technical upgrades, but rather these are deeply social processes tied to politics and economics, but also to values and beliefs of different stakeholder groups affected by the process and its outcomes. Such a perspective helps us to understand why justice considerations should be central to energy transition debates.

Put simply, justice is about shared judgments of what is right and desirable. Scholars argue that the transition must be "humanised", meaning that it should be guided by the principle of fairness, so that the most vulnerable groups are not marginalised and inequalities are not worsened (Jenkins et al., 2012). And while low carbon systems are often assumed to be fairer, we need to remember that even a low carbon transition can concentrate environmental risks or unfair outcomes on less powerful actors, such as vulnerable social groups or remote communities.

The idea of a just transition began in labour movements but now it is closely linked to environmental, climate, and energy justice. It underscores that while cutting emissions is urgent, the way we do it must be equitable, both in terms of the outcomes and implementation. When attempting to assess justice, we can ask questions such as: who benefits, who bears the costs, and how are decisions made? Justice has different dimensions which help us to examine whether the benefits and burdens are fairly distributed in society, whether decisions are made inclusively and transparently, and whether marginalised or vulnerable groups are respected and acknowledged in the process (Zimm et al., 2024).

When considering justice in energy transitions, we can also reflect on how harms are being repaired, whether cross-border and future responsibilities are recognised, or whether different kinds of knowledge are equally valued. Reflecting on these issues will help us both to identify potential injustices and provide guidance for reparative action. However, when such justice concerns are ignored, public resistance can grow, significantly slowing down or even halting some transition trajectories. As can be seen in different examples of social opposition to energy infrastructure projects, such pushbacks frequently signal unaddressed injustices (Brisbois and Cantoni, 2025).

A relevant and timely example is the expanding lithium-ion battery sector in Finland. Global decarbonisation goals have positioned Finland as a strategic hub for Europe's battery supply chain. Finland's minerals and industrial know-how provide excellent economic opportunities—an estimated €6–9 billion in potential investments and up to 20,000 jobs in the next five years (Finnish Battery Industries, 2025). However, at the same time, rapid growth raises complex justice challenges.

Industrial expansion has triggered conflicts and social opposition, especially in sensitive places, such as in the close proximity of nature conservation areas, Sámi reindeer herding territories, tourism and cultural heritage sites, or lake regions with holiday homes (Eerola, 2024). Environmental risks have sparked "green-on-green" conflicts (climate goals versus nature protection), exacerbated by past polluting incidents like the Talvivaara mine leak in 2012, when around 1,000 hectares of rivers and lakes were contaminated by toxins.

Citizens and organisations opposing further industrial expansion criticise untransparent procedures, including opaque permitting, centralised decision-making, and limited local influence—factors which have undermined trust and damaged the social license to operate. What further fuels the opposition is the perceived misrecognition of local values and property rights, or violation of Indigenous rights, especially in Lapland. Additionally, with the growing investment by transnational companies, economic tensions arise over who bears the most burdens of such investments, and who benefits from them (Leino, 2024; Similä and Wallen, 2023). Overall, as different studies show, such opposition can be expected to grow along with the intensified investments across the whole supply chain of lithium-ion batteries in Finland, slowing down or inhibiting the transition process.

To address these concerns, justice should be placed at the very centre of public debates. This means inviting citizens or marginalised social groups to actively participate in the decision-making process from its early stages to ensure that different interests and values are taken into consideration, all affected stakeholders can actively participate and be heard, and that local contexts and rights are respected. Local opposition demanding justice should not be seen as an obstacle to overcome—it is the foundation for a transition that people trust, support, and help to build. When justice concerns are addressed early and transparently, the path to a clean energy future becomes more durable, more democratic, and more widely shared.

5.3 Protecting climate, land, nature, and water

While the planetary boundaries framework highlighted global ecological limits above, this section approaches these issues from a complementary angle, focusing on the technical, operational, and local environmental impacts of the energy transition, as well as the trade-offs that arise when implementing solutions in specific sectors.

5.3.1 Climate

Energy supply is the leading contributor to global warming, accounting for over 75% of greenhouse gas (GHG) emissions through fossil fuel combustion (Kunak, 2025). The direct environmental impacts associated with energy generation can be grouped into three main life-cycle stages: upstream processes related to the energy infrastructure (extraction, manufacturing, and construction) including the possible fuel cycle (extraction, production, processing, and delivery); operation (combustion, maintenance, and other operational activities); and downstream processes (dismantling, decommissioning, and recycling).

Figure 5.2 compiles information on the ranges of GHG emissions from electricity production using different fuels and technologies. For coal, oil, and natural gas-based electricity, emissions are primarily associated with combustion. Variations in emission ranges are influenced by factors such as gas flaring during extraction, methane leakage, regional conditions, and the technologies employed. The implementation of carbon capture and storage (CCS) can substantially reduce emissions; however, approximately 10–15% of the total GHG emissions remain embedded in the fossil fuel supply chain. For fossil fuel-based electricity with CCS, emission variability depends on capture rates, operating conditions, and system efficiency.

Electricity generation from peat has a higher GHG impact than many other fossil fuels because peat is a slowly renewable resource that takes centuries to form. The role of peat is important only to Finland which is one of the few countries still using significant amounts of peat to produce energy. Emissions from the use of peat account for drainage, extraction, transport, and combustion, with differences largely driven by peatland location. In the case of waste incineration, emission ranges depend on waste composition and system efficiency, with a significant share of GHG emissions originating from the plastic fraction of the waste stream. For biogas-based electricity, combustion is often considered carbon-neutral due to biogenic CO_2. Therefore, the emission variability is mainly influenced by the feedstock type, transportation, and methane leakage especially from anaerobic digestion.

For renewable electricity production, the majority of GHG emissions are accounted for during the construction phase. This is particularly true for hydropower and onshore and offshore wind power technologies. For biomass-based electricity, GHG emissions vary significantly depending on the feedstock type (dedicated or non-dedicated biomass), supply chain characteristics, land use change, impacts on carbon stocks, and system efficiency. In the case of nuclear power, the upper range corresponding to the fuel supply chain contributes the largest share of GHG emissions. For solar power, emission ranges reflect differences between mono-crystalline and multi-crystalline silicon technologies. Therefore, multi-crystalline PV has been widely phased out from solar PV manufacturing (Fraunhofer, 2025). With continued technological advancements and optimised management practices, emissions could decline from about 27 gCO2 eq/kWh as of the early 2020s to values below 10 g CO2 eq/kWh from 2040 onwards (Dashti et al., 2025).

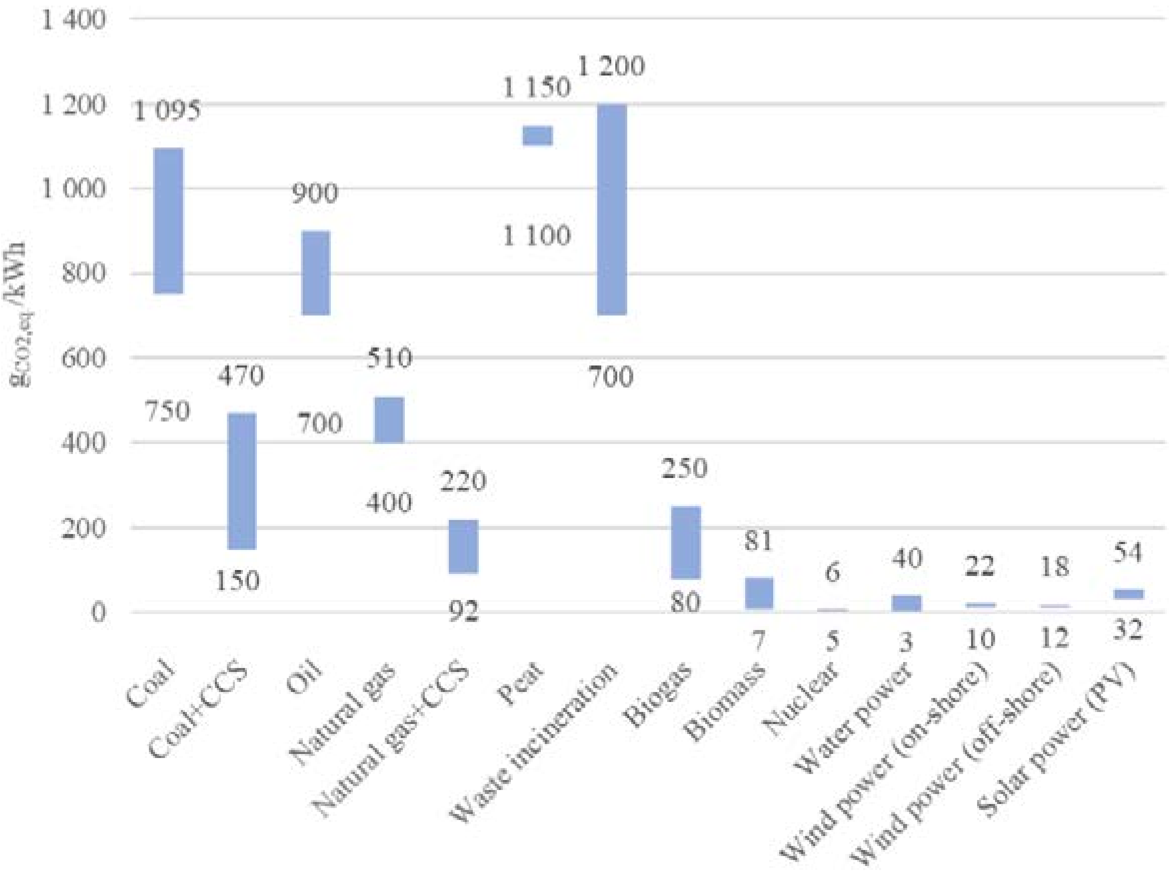


Figure 5.2. A compilation of greenhouse gas emission factors for electricity generation (CCS=-carbon capture and storage, PV=Photovoltaic) (UNECE, 2021; Gibon and Hahn Menacho, 2023; Kadiyala et al., 2016; Giuntoli et al., 2017; Paolini et al., 2018; Han et al., 2023; Murphy et al., 2015; Gan et al., 2024; Li et al., 2025).

5.3.2 Land use change and biodiversity implications

This section examines land-use change and the biodiversity implications of the energy transition, while considerations related to forest use and carbon sinks are discussed in Section 5.5.

Land is also a limited resource globally. Approximately 50% of habitable land is already reserved for food production and human activities have altered over 75% of all land areas (IPBES, 2019). Therefore, land needs and possible locations for energy systems play an important role to avoid competition with food production, to avoid deforestation and further loss of biodiversity. Biodiversity is declining faster than ever before in human history. The main direct biodiversity loss drivers are land and sea use and change, direct exploitation, climate change, pollution and invasive alien species (Fig. 5.3). For terrestrial ecosystems land use and its changes are the most important drivers of biodiversity loss (IPBES, 2019).

Figure 5.3. Direct and indirect drivers of nature loss. Examples of global declines in nature, emphasising declines in biodiversity, that have been and are being caused by direct and indirect drivers of change (IPBES, 2019).

Land use is linked to different life cycle stages of energy production e.g. via mining, manufacturing and production facilities, biomass and fuel production, and end-of-life operations. Important factors influencing the magnitude of biodiversity impacts via land use are how much land is needed, what kind of land use is involved (can the land still preserve some biodiversity levels or is everything completely lost), and where the land use takes place geographically. Similar land use leads to significantly different biodiversity impacts in different locations.

Globally, impacts are the highest close to equator and in islands, where biodiversity levels are typically high, there is a high degree of endemism and ecosystems are also under pressure from human activities (Verones et al., 2022). However, safeguarding local nature is equally important everywhere, as ecosystem resilience, food production, cultural values, and security of supply are closely tied to biodiversity at the national and local levels. These geographical differences in biodiversity impacts also raise questions of responsibility and burden sharing, particularly where land-use pressures are driven by global supply chains and international consumption.

Therefore, the design of energy systems must address climate change and biodiversity loss as closely interconnected challenges rather than treating decarbonisation as a standalone objective. A sustainable energy transition requires operating within environmental limits across climate, biodiversity, and land use simultaneously. As renewable energy deployment accelerates, the impacts of the energy infrastructure on ecosystems, habitats, and landscape use must be systematically assessed and carefully managed.

Land-use impacts are a critical consideration in the energy transition and must be explicitly addressed in energy planning. All energy sources require land, but their impacts vary significantly

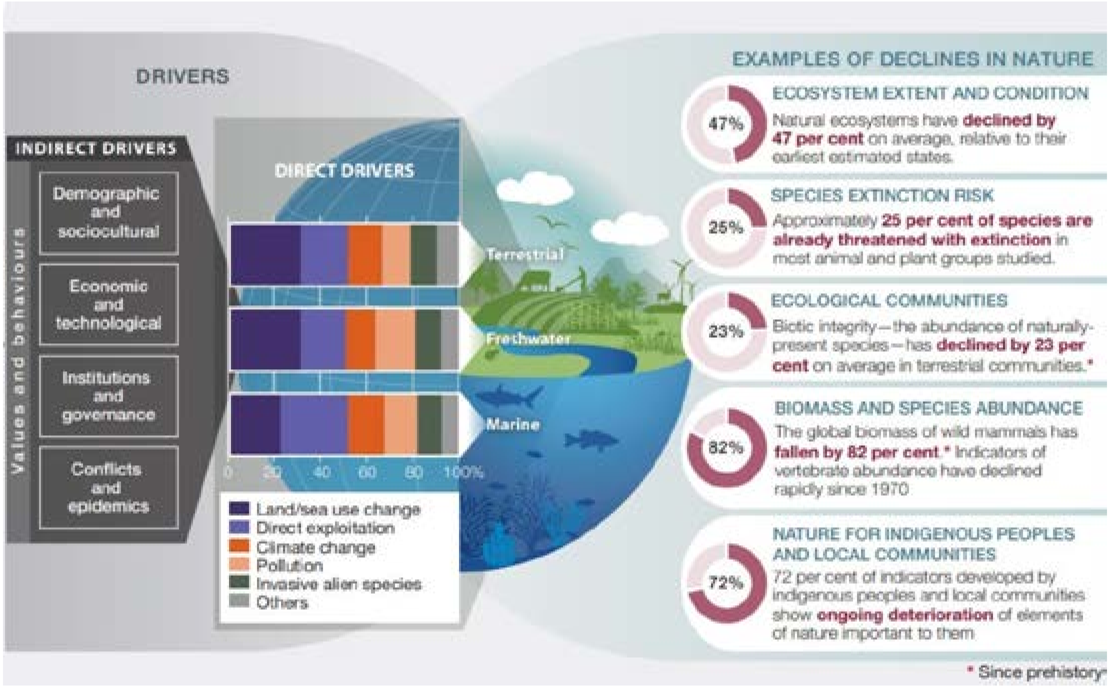


Figure 5.3. Direct and indirect drivers of nature loss. Examples of global declines in nature, emphasising declines in biodiversity, that have been and are being caused by direct and indirect drivers of change (IPBES, 2019).

depending on the technology, location, and local ecological and social conditions. Land-use intensity, defined as the area required per unit of energy produced, differs widely between energy sources and is strongly influenced by resource availability, such as wind conditions or solar irradiation (see Figure 5.4).

Fossil fuel production typically has large and highly disruptive land-use footprints, affecting soil, water systems, and ecosystems. Among low-carbon energy sources, nuclear power generally has the smallest land-use intensity, while dedicated biomass production has the largest land-use impact per unit of energy produced. Wind and solar energy usually have relatively small direct land footprints but can influence vast areas of land.

This is particularly relevant given Finland's ambition to produce approximately 10% of the European Union's green hydrogen by 2030 (TEM, 2023). The total land required depends on how much wind power can be installed within a given area. If wind turbines must be spaced further apart or conditions limit how many turbines can be built in one location, larger land areas are needed to produce the same amount of electricity. Depending on site conditions and planning choices, the total land needed to generate wind electricity for hydrogen production can vary by an order of magnitude, from 8,000 to 25,000 km2, the maximum end approaching the scale of Finland's current arable land area (Paulomäki et al., forthcoming).

Land use is a central consideration in the large-scale deployment of renewable energy requiring careful spatial planning and land-use optimisation. From a policy perspective, technology choices, site selection, and integrated land-use strategies are critical.

Prioritising low-impact locations, assessing trade-offs between climate, biodiversity, and land use, and combining energy production with other land uses, such as agriculture or forestry, can help ensure that energy system expansion advances both decarbonisation and nature protection goals. Integrated approaches, including co-location strategies such as wind power in managed forests, solar combined with peatland restoration, or agrivoltaic systems, can further enhance land-use efficiency while reducing environmental pressures and climate change.

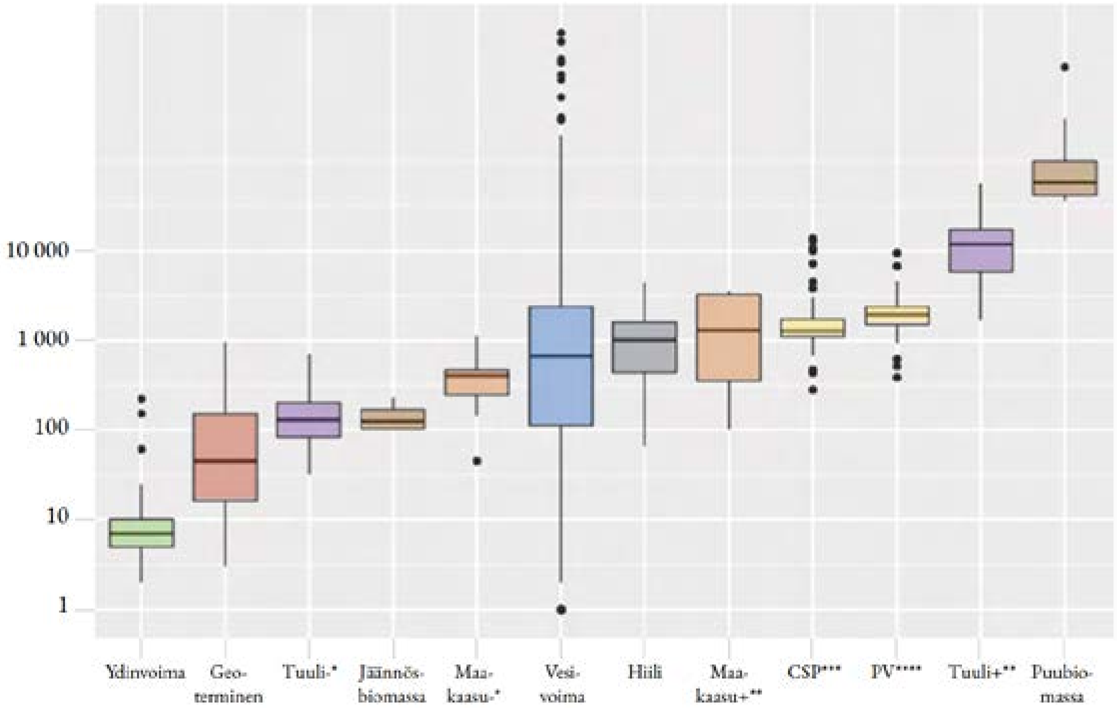


Figure 5.4. Land use intensity of electricity production (LUIE), 100 ha/TWh corresponds to 1 km2/TWh and 1 m2/MWh. Boxes represent the inter-quartile range with the median as the middle bar. Whiskers extend to the highest or lowest data point that is within 1.5 times the inter-quartile range, points outside this range represent outliers. Electricity sources: nuclear energy (Nuclear), geothermal energy (Geo), wind energy with footprint only (Wind–), natural gas footprint only (NG–) and including spacing (NG+), hydroelectric power for single purpose dams (Hydro), coal (Coal), concentrating solar power (CSP), ground-mounted photovoltaic solar energy (PV), wind energy with footprint (Wind-) and spacing (Wind+), and residual biomass (BioRes) and dedicated biomass (BioDed). (Lovering et al., 2022).

Energy production affects not only how much land is used, but also the condition and continuity of habitats. Land is required for fuel extraction, energy infrastructure, material sourcing, and waste management, and these activities can alter natural landscapes. For example, wood- and peat-based energy rely directly on land resources and can substantially alter habitats through extraction and drainage. In contrast, harvesting renewable energy such as wind energy requires a vast land area, but typically the directly transformed area is small. However, even when physical footprints are limited, associated infrastructure, access roads, and grid connections can fragment habitats and disturb species. As habitats shrink or become disturbed, populations may decline and ecosystem resilience may weaken. Energy generation, e.g. wind turbines can also impact on biodiversity in surrounding land areas via a displacement effect which means that some species prefer to keep a distance from wind turbines which limit their habitats (Tolvanen et al., 2023). The type, scale, and management of land use therefore determine how energy production translates into biodiversity impacts.

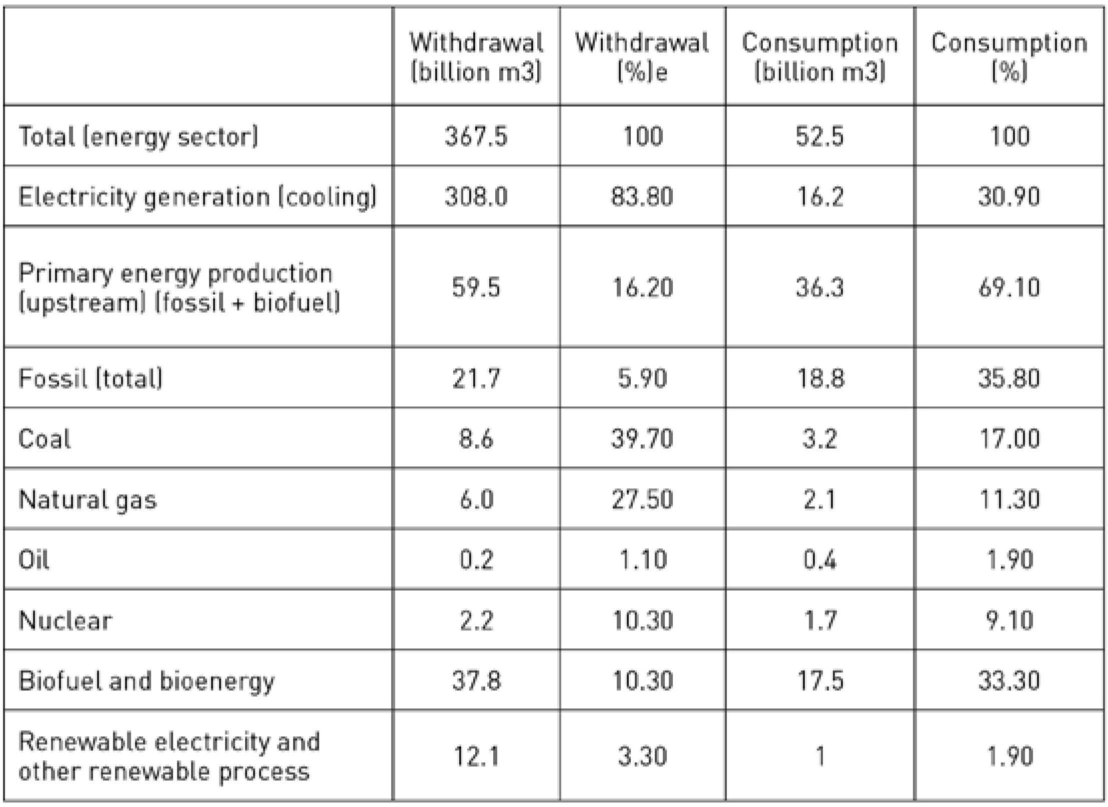
Direct exploitation can be linked to the use of natural resources as a feedstock or material for energy systems. Energy systems can also increase species mortality via collisions with power lines or wind turbines (Tiago et al., 2018), for example. Pollution category consists of different kinds of environmental impacts caused by pollutants such as acidification, eutrophication, and microplastics. Acidification is typically closely associated with energy production through combustion processes, while eutrophication is linked to fertilizer use, which can be relevant for dedicated energy crops. In addition, activities such as coal mining can also release phosphorus into the environment, contributing to eutrophication. Invasive alien species can pose a particular risk through the long-distance transport of fuels or feedstocks, and production sites may also serve as pathways for their spread.

5.3.2 Water

Following the assessment of climate change and land-use impacts on the energy system, it is essential to evaluate the implications of water use as well. Although the Earth possesses an abundant quantity of water, only approximately 3% is available as freshwater. Consequently, water is a critical resource whose conservation and end-use must be managed with great care. Water plays a direct role in the operation of the energy system. For example, thermal power plants, including coal, natural gas, biomass, and nuclear facilities require substantial volumes of water for cooling and steam condensation (Dahl Larsen & Drews, 2019). In addition, fossil fuel extraction and biomass processing require considerable water consumption (IEA Bioenergy, 2024). Conversely, the provision of water depends on energy inputs for extraction, treatment, pumping, and distribution, a relationship commonly referred to as the water–energy nexus (Lee et al., 2017). The energy sector constitutes a major industrial water user, accounting for an estimated 10—15% of global freshwater withdrawals, and it is projected to double by 2030 (IEA, 2023b). Moreover, water use in energy supply can adversely affect water quality through chemical contamination, thermal pollution, and hydrological flow alteration.

In the energy sector, freshwater withdrawals are substantially higher than freshwater consumption, primarily because most cooling water is returned to the source, as illustrated in Table 5.1. Cooling for electricity generation, including both thermal and nuclear technologies, constitutes the dominant component of water withdrawals in the sector. While primary energy production is the main contributor to water consumption, largely due to processes such as fossil fuel extraction and

Table 5.1. Global energy sector water use by category (IEA, 2023b; Planete energies, 2025)



	Withdrawal (billion m3)	Withdrawal (%)e	Consumption (billion m3)	Consumption (%)
Total (energy sector)	367.5	100	52.5	100
Electricity generation (cooling)	308.0	83.80	16.2	30.90
Primary energy production (upstream) (fossil + biofuel)	59.5	16.20	36.3	69.10
Fossil (total)	21.7	5.90	18.8	35.80
Coal	8.6	39.70	3.2	17.00
Natural gas	6.0	27.50	2.1	11.30
Oil	0.2	1.10	0.4	1.90
Nuclear	2.2	10.30	1.7	9.10
Biofuel and bioenergy	37.8	10.30	17.5	33.30
Renewable electricity and other renewable process	12.1	3.30	1	1.90

biomass cultivation. Although solar and wind technologies require relatively small amounts of water during manufacturing, these uses are shown within the renewable energy category presented in Table 5.1. However, in the context of thermal electricity generation, if fossil and nuclear energy could be replaced and operations were primarily powered by renewable electricity, water consumption could be reduced by 98% and water withdrawals by 95%, according to a study comparing the water footprint of 13,863 thermal power plant units (Lohrmann, 2019). Currently, global hydrogen production requires approximately 1.5 billion m3 of freshwater. This demand is projected to increase to about 3 billion m3 by 2030 and to around 10 billion m3 by 2050 for green hydrogen production alone (IEA, 2023b).

5.4 The role of bioenergy and biomass

Global bioenergy consumption saw a slight increase in 2024, reaching just over 60 EJ. Traditional solid biomass accounted for one-third (20 EJ) of this total, while modern bioenergy—including solid bioenergy (34 EJ), liquid biofuels (4 EJ), and biogas (2 EJ)—made up the remainder (IEA, 2025a). Solid bioenergy now represents 85% of the modern bioenergy demand. Sourced from materials such as forestry residues and municipal solid waste, solid bioenergy is primarily used for heating, with smaller roles in electricity generation and transport fuels. The expansion of biofuels is limited by competing land uses. By 2050, the total bioenergy and waste consumption could exceed 100 EJ, aligning with conservative estimates of the sustainable global production potential (IEA, 2025a), which is considered the sustainable bioenergy supply limit (Creutzig et al., 2015).

The EU enforces the most stringent sustainability criteria for bioenergy, with the latest standards outlined in REDIII. These criteria mandate greenhouse gas emission reductions and impose land use restrictions on the production of biomass used for bioenergy. International voluntary certification systems further verify sustainability, incorporating social and administrative requirements. For woody biomass, compliance also necessitates sustainable forest management and adherence to the cascading use principle, both of which enhance carbon sequestration and biodiversity by supporting diverse forest structures and functions.

Biofuels remain a key alternative to using fossil oil in transport, but its expansion must respect sustainability limits, including land availability, impacts on food production, biodiversity, water use, and the carbon balance, to ensure that it truly contributes to climate mitigation without undermining other planetary boundaries. While liquid biofuels currently dominate in non-fossil road transport, electric vehicles are expected to lead passenger road decarbonisation. Growth in liquid biofuels is now focused on aviation—through sustainable aviation fuels (SAFs)—and shipping, with methanol, hydrogen, and ammonia (Kian, 2026). EU measures such as ReFuelEU Aviation, FuelEU Maritime, and the Emissions Trading System will increase blending mandates for liquid biofuels by 2035. By the 2040s, synthetic fuels using hydrogen and captured biogenic CO_2 are expected to become a significant SAF source. Current policies support low-emission fuels, projected to meet nearly 10% of aviation and 15% of shipping energy demand by 2050 (IEA, 2025a).

Biogas is the fastest-growing form of bioenergy, with an increasing share being upgraded to biomethane. This growth is driven by supportive policies in several countries, reflecting biomethane's value as a direct substitute for natural gas and its benefits for energy security. Currently, only about 5% of the global sustainable potential for biogas and biomethane is utilised. The European Union leads in usage, employing approximately 40% of its biogas potential and setting ambitious biomethane targets to strengthen domestic energy sources and reduce the reliance on Russian gas (IEA, 2025a).

Electrification significantly enhances efficiency and reduces emissions, but it cannot fully decarbonise certain hard-to-abate sectors, such as industrial processes requiring high-temperature heat. Buildings and industries connected to natural gas infrastructure

may partially transition to biomethane or synthetic gases. Globally, district heating systems are shifting from fuel-based solutions to integrated approaches, including solar thermal, geothermal, heat pumps, and waste heat utilisation. In countries with substantial heating demand, such as Finland, bioenergy will remain a key component of district heating to meet peak winter consumption. Additionally, combined heat and power plants can utilise bioenergy for electricity generation, providing essential balancing capacity for variable renewable energy production. See section 7.1.1 for technologies.

5.5 Managing carbon wisely

This section focuses on sustainability aspects, with Section 7.2.2 addressing technological solutions for carbon. In Finland, land-use changes are a key factor in managing carbon effectively. However, the conversion of forest or other biomass-based resources to energy or biofuels and -chemicals releases biogenic CO_2, which can be part of a renewable carbon cycle through carbon capture and utilisation (CCU). Modern societies rely heavily on fossil-based products, and without sustainable alternatives for these essential materials, climate mitigation remains difficult—particularly in hard-to-abate sectors. CCU is often combined with low-carbon hydrogen (H_2) production to produce these alternatives. Low-carbon H_2 and its derivatives are often referred to as Power-to-X (PtX) products. Another viable option to mitigate emissions is to utilise technical carbon sinks, such as carbon capture and storage (CCS), or to increase natural sinks, such as forests. Here, we highlight the main findings and policy-relevant insights without detailing the calculation methods. The scenarios presented are dependent on carbon balance calculations, which have recently changed and might continue to change when new information becomes available.

To understand how to manage carbon wisely, it is important to understand some key terminology. Carbon dioxide removal (CDR) encompasses methods that extract CO_2 directly from the atmosphere and sequester it in long-term reservoirs, thereby delivering net-negative emissions. These approaches include biological (e.g., afforestation), geological, and ocean-based methods and are critical for compensating residual emissions and achieving net-negative climate targets. CCU captures CO_2 from either point sources or the atmosphere but diverts it into productive applications rather than permanent storage (Mertens et al. 2023). CCU pathways include mineralisation for building materials, synthetic fuels, polymers, and chemical intermediates. The climate performance of CCU varies widely. Carbon Capture and Storage (CCS) involves capturing CO_2 at point sources, such as power plants or industrial facilities, and storing it in geological formations (e.g., depleted reservoirs or saline aquifers). Unlike CDR, CCS does not remove atmospheric CO_2; its role is to avoid new emissions by preventing the release of concentrated industrial CO_2 streams.

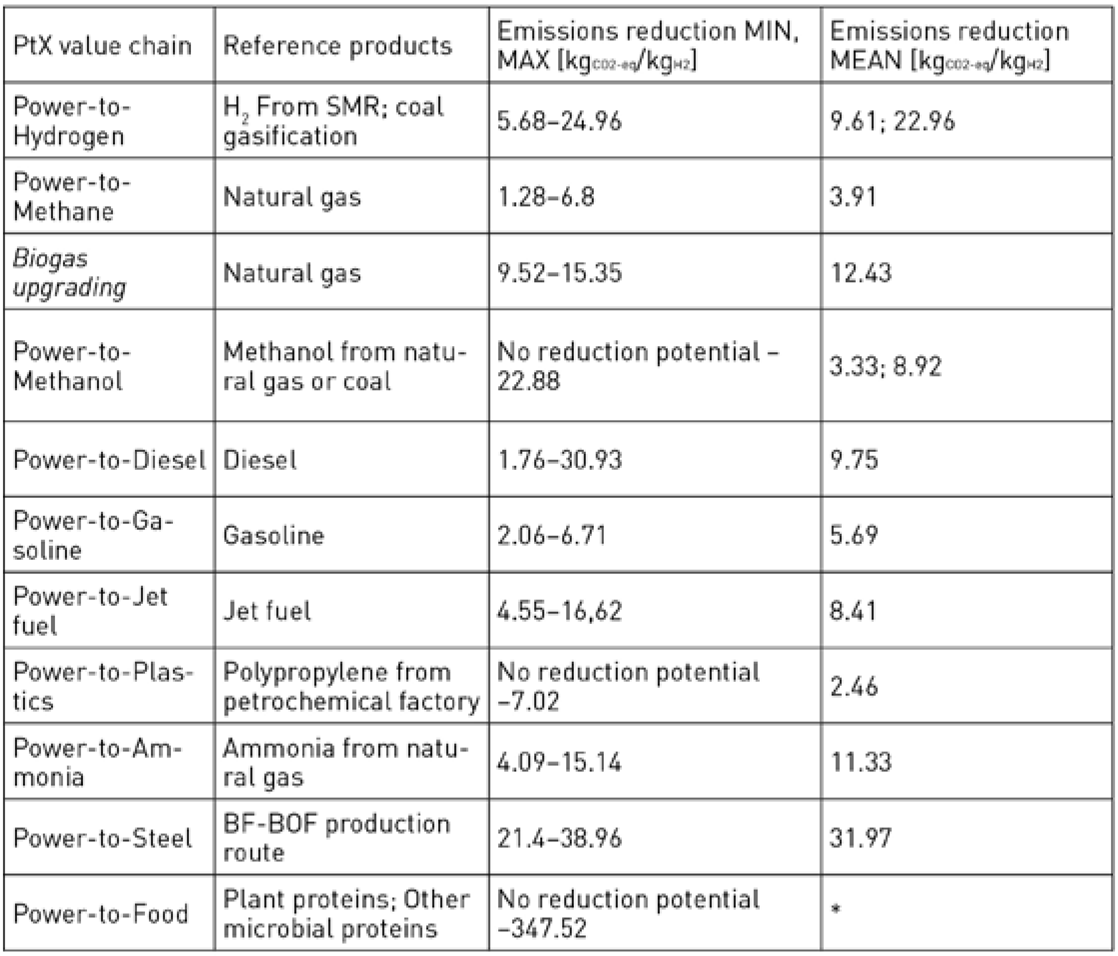
Each member state in the EU is responsible for technological solutions required to bring its fossil emissions to zero and thus, bears the cost for its national actions. How to share the costs for carbon management has not yet been agreed. Some EU countries e.g. Denmark and Sweden have started CCS with national funding, while no EU-wide funding plan has yet been accepted. EU distributed LULUCF burdens for each member states are based on historical values, and the greatest current problem is that a large number of the EU member states do not properly measure their LULUCF emissions but instead rely on fallback estimates of kg CO2 e/ha.

Finland's forest areas remained a carbon sink throughout the period from 1990 to 2024 with annual forest growth exceeding 100 million m3; however, the strength of this sink has decreased significantly in recent years (LUKE, 2025). The Finnish climate panel (Seppälä et al., 2026) evaluated different forest cutting scenarios from biodiversity, carbon sink and emission reduction target perspectives. They found that, at the lowest harvesting level examined—60 million m^3 per year, and possibly slightly higher—it is possible to meet both current climate targets while also enhancing biodiversity-relevant forest structures. Harvesting 70 million m^3 per year keeps forests as a clear carbon sink but is insufficient to meet the EU's 2030 land-use sector target or Finland's 2035 carbon-neutrality goal. If harvesting levels are not reduced while protected areas expand, an annual harvest of 70 million m^3 increases pressure on commercial forests and weakens long-term carbon sink development. At the same time, the positive biodiversity trends observed at approximately 60 million m^3 per year stagnate or decline. Increasing harvest levels to 80 million m^3 annually would be incompatible with both climate and biodiversity objectives in the short term and would further undermine their achievement in the long term (Seppälä et al., 2026).

Another report by the Finnish Climate Panel (Kujanpää et al., 2023) highlights that technological carbon sinks (bioenergy CCS) can support Finland's climate goals after 2030, but they cannot replace or delay other climate measures, particularly as Finland is already lagging behind the EU's 2030 targets for the Effort Sharing and Land Use sectors. Strengthened action is also required to reach the 2035 carbon-neutrality target. The Climate Panel notes that producing 5–6 Mt of negative emissions would help ensure this goal is met. Capturing and storing CO_2 from Finland's two to three largest biogenic emitters—mainly pulp, paper, and bioproduct mills—could provide about 5 Mt of technological carbon sinks. Achieving this would require annual funding of roughly €600–700 million, if the state covered all costs of capture, compression, transport, and sequestration.

PtX products can help in mitigating emissions through substituting fossil fuel-based alternatives and thus reducing the fossil dependence. Substituting fossil fuels by using CCU applications can have a higher climate mitigation potential than CCS, but it is dependent on the used energy mix (Krogh et al., 2024). A meta analysis of several PtX pathways with a comparison of the climate reduction potential was carried out by Sillman et al. (2024). The study includes also non CCU PtX pathways. The results show that using H2 to make steel gives the biggest climate benefit, followed by making ammonia, using H2 directly, and upgrading biogas (see Table 5.2). Producing protein through the Power-to-Food pathway also has huge potential, especially compared to meat, but it depends on what it replaces. Making fuels or plastics from H2 and CO2 helps less because capturing and processing CO_2 is energy intensive. Still, every option using either nuclear or renewable energy can provide extensive emissions reductions when replacing conventional fossil-based products. The type of electricity used is also very important. If H2 is made with renewable or nuclear power, the climate benefits are large when substituting fossil-based products. If the electricity comes from fossil fuels, the benefits can disappear. In summary, renewable-based PtX product alternatives for fossil-based ones can provide environmentally sustainable alternatives, but there is a difference in what is produced and what is substituted.

Table 5.2. Emissions reduction potential of several Power-to-X pathways. Renewable energy or nuclear energy used to produce hydrogen through water electrolysis (reproduced from Sillman et al. 2024).



PtX value chain	Reference products	Emissions reduction MIN, MAX [$kg_{CO2\text{-}eq}/kg_{H2}$]	Emissions reduction MEAN [$kg_{CO2\text{-}eq}/kg_{H2}$]
Power-to-Hydrogen	H_2 From SMR; coal gasification	5.68–24.96	9.61; 22.96
Power-to-Methane	Natural gas	1.28–6.8	3.91
Biogas upgrading	Natural gas	9.52–15.35	12.43
Power-to-Methanol	Methanol from natural gas or coal	No reduction potential – 22.88	3.33; 8.92
Power-to-Diesel	Diesel	1.76–30.93	9.75
Power-to-Gasoline	Gasoline	2.06–6.71	5.69
Power-to-Jet fuel	Jet fuel	4.55–16,62	8.41
Power-to-Plastics	Polypropylene from petrochemical factory	No reduction potential –7.02	2.46
Power-to-Ammonia	Ammonia from natural gas	4.09–15.14	11.33
Power-to-Steel	BF-BOF production route	21.4–38.96	31.97
Power-to-Food	Plant proteins; Other microbial proteins	No reduction potential –347.52	*

6. SKILLS AND EDUCATION

Authors: Johanna Naukkarinen, Miika Marttila, Minna Havukainen and Hanna Paulomäki

6.1 The need for new skills for the sustainable energy transition

The energy transition requires a diverse set of skills, and stakeholders to develop sustainable energy systems. This sets pressure and places demands on engineering education in two ways. First, there is a need to understand what sustainable energy systems—those that operate within planetary boundaries while generating well-being—will look like. Second, there is a need to develop the expertise required to design, operate, and protect infrastructure under extreme conditions, while integrating biodiversity and social considerations into energy planning. These challenges have also been identified by industry stakeholders as critical gaps in the skills and education needed to support the energy transition (Paulomäki and Järvinen, 2025).

As renewable energy grows and electrification leads to increasing demand fluctuations, engineers must adapt to dynamic systems and complex trade-offs. They need to furthermore be equipped with the knowledge and skills to navigate political, economic, societal, technological, and environmental challenges, including complex regulations, fluctuating energy prices, and rapid technological changes. This includes both technical competencies and non-technical skills, such as communication and teamwork. Energy education must therefore prepare professionals to address ecological, social, and economic objectives simultaneously, avoiding "carbon tunnel vision" (Fig. 6.1) in which decarbonisation is pursued at the expense of nature or human rights (Paulomäki and Järvinen, 2025).

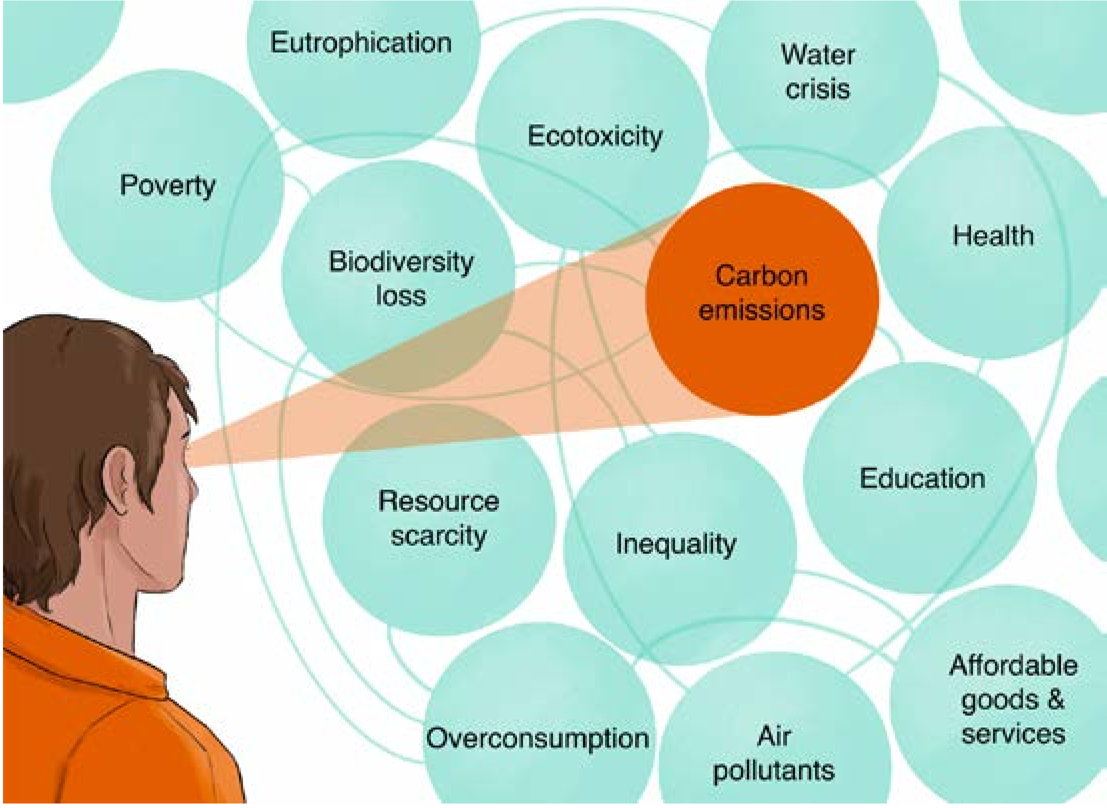


Figure 6.1. Carbon tunnel vision (Paulomäki and Järvinen, 2025). Copyright: Maija Karala.

Technologically, expertise is needed in grid flexibility, energy storage, and integrating variable renewable energy, while environmental literacy, sustainable mining, lifecycle impacts, and biodiversity are essential for holistic planning. Overall, stakeholders have emphasised that education and training must develop both technical competencies and broader sustainability, ecological, and social awareness to prepare a workforce capable of designing sustainable, adaptive, and socially responsible energy systems (Paulomäki and Järvinen, 2025). Similar findings were reported in a study commissioned by Engineers in Finland (TEK, 2022), which showed that the green transition increases the need for teamwork, communication skills, adaptive, and continuous learning, while the mathematical and technical core of engineering remains essential.

6.2. Energy literacy, digital learning, and new sustainable energy business

Education has taken on an increasingly important role in the energy transition alongside technological advancements that create new opportunities (Sovacool, 2019; Michel, 2020). One of the main emphases in energy education is to advance energy literacy skills in engineering education. Energy literacy involves understanding how energy operates in terms of natural sciences, and within societal contexts. McCaffrey (2015) defines an energy-literate individual as someone who can: (a) recognise the main functions of various energy systems (such as fossil fuels, nuclear power, hydropower, solar, biomass, and geothermal energy); (b) explain the origins of different energy forms and the processes by which they are extracted or transported; (c) assess the social and environmental impacts of energy sources and their uses; (d) identify reliable information related to energy; and (e) conceptualise and interpret the role of energy within society.

Between 2010 and 2024, the world experienced a growing shortage of skilled professionals capable of supporting renewable energy systems, with even greater deficits anticipated in the coming years (Ram et al., 2022). Current evidence suggests that the swift global uptake of renewable energy is not adequately matched by shifts in higher education. Many universities continue to emphasise coal and petroleum studies, meaning they fail to produce the skilled clean-energy workforce required worldwide—particularly in developing countries, where this delay may significantly hinder the transition (Vakulchuk & Overland, 2024). Governments aiming to accelerate the energy transition should prioritise investments in higher education, rather than relying solely on financial incentives for industry (Gui & MacGill, 2018).

This has now been noticed as there are several new study programmes in the Nordics that have a greater focus on renewable energy technologies and solutions that promote and strengthen education. Over the past decade, Finnish educational foresight has emphasised the growing importance of renewable energy sources, energy storage, decentralised production, and intelligent energy networks (Leveälahti et al, 2019). These programmes aim to raise awareness of the advantages of renewable energy and the importance of environmental protection (Senthil, 2022). For instance, virtual laboratories have significantly improved students' enthusiasm, understanding, and familiarity with renewable energy. New learning environments, such digital learning environments offer interactive and easily accessible platforms that allow learners to explore renewable energy systems and microgrids through hands-on experimentation (Guo, 2022).

Strengthening collaboration between academic institutions, civic society and industry is essential for genuine and engaging interaction with communities in large-scale renewable energy deployment, and development of sustainable energy business solutions, which are able to contribute to advancing climate change mitigation. This supports the creation of new companies in the renewable energy sector and encourages more efficient energy management practices within industrial production (Heras-Saizarbitoria et al., 2018; Garrido-Yserte & Gallo-Rivera, 2020). Beyond fostering new enterprises and improving production processes, education also enables the emergence of energy communities, off-grid solutions, and innovative organisational models that empower citizens and stimulate novel social and technological ventures in the energy field (Gibellato et al., 2023).

6.3. Advancing sustainability and diversity in higher education in Finland

The official guidelines by the Finnish national agency for education (OPH) highlight responsibility for the environment, well-being, and a sustainable future in teaching (OPH, 2023). Knowledge of sustainability principles and their use as guiding goals for energy system management is essential, especially given the connections between the climate crisis, energy use, and growth (Leveälahti et al., 2019).

Higher education institutions must prepare future professionals not only to critically assess the desired direction of the energy transition, but also to manage its complex processes, rather than focusing solely on adapting to new technologies (Leveälahti et al., 2019; OPH, 2023). Interdisciplinary education should be developed across fields to provide a broad understanding of sustainability and the related competences needed in specific domains (OPH, 2023). Taken together, these directions suggest that meeting the changing requirements of the energy sector calls for both new content and new ways of structuring and integrating learning across disciplines.

Research indicates that the mainstreaming of sustainability education in engineering education is currently hindered by a lack of clear and systematic steering and the lack of shared methods for monitoring and reporting progress (Routaharju, 2025). Addressing these obstacles is necessary to develop engineering education and prepare future professionals better for the advancement of the energy transition. In sustainability education for younger generations, research calls for educational models that integrate several Science, Technology, Engineering, Arts, and Mathematics (STEAM) subjects in order to address multiple dimensions of sustainability simultaneously, thus enhancing a holistic view (Naukkarinen & Jouhkimo, 2021). When developing these models, special attention should be paid to reaching out to all types of students. For example, factors such as gender and educational orientation affect the students' perceptions of and attitudes towards sustainability, resulting in sustainability education activities appealing mostly to the academically oriented girls and having little impact on vocationally oriented boys (Naukkarinen & Jouhkimo, 2021).

6.4. Multidisciplinary skills and expert teams and challenges in current education

The energy transition and societal changes are reshaping the skills needed by experts, requiring not only strong technical competence but also broad non-technical skills such as communication and collaboration. This highlights the growing importance of multidisciplinary teamwork, where engineers work alongside economists, biologists, social scientists, etc. to develop optimal energy solutions. Each team member is expected to have a T-profile (Fig. 6.2): deep expertise in their own field combined with a broad understanding of the energy system, creating collective competence capable of addressing complex technical, environmental, and social challenges (Paulomäki and Järvinen, 2025).

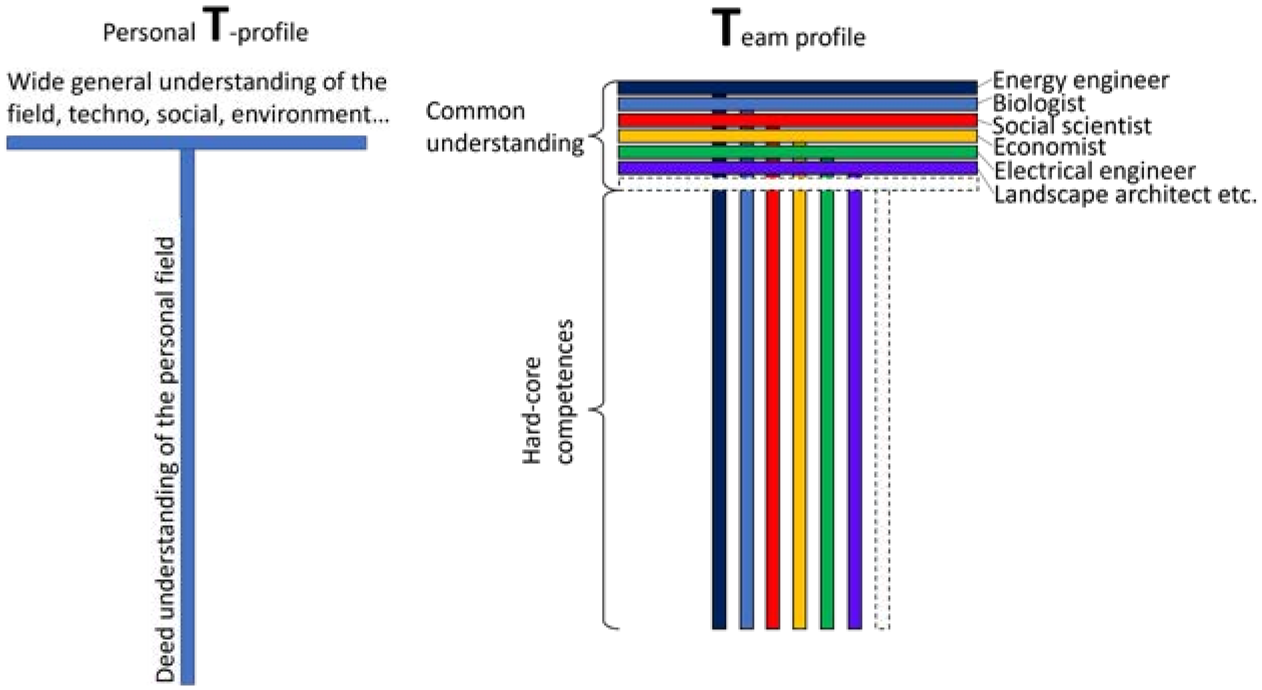
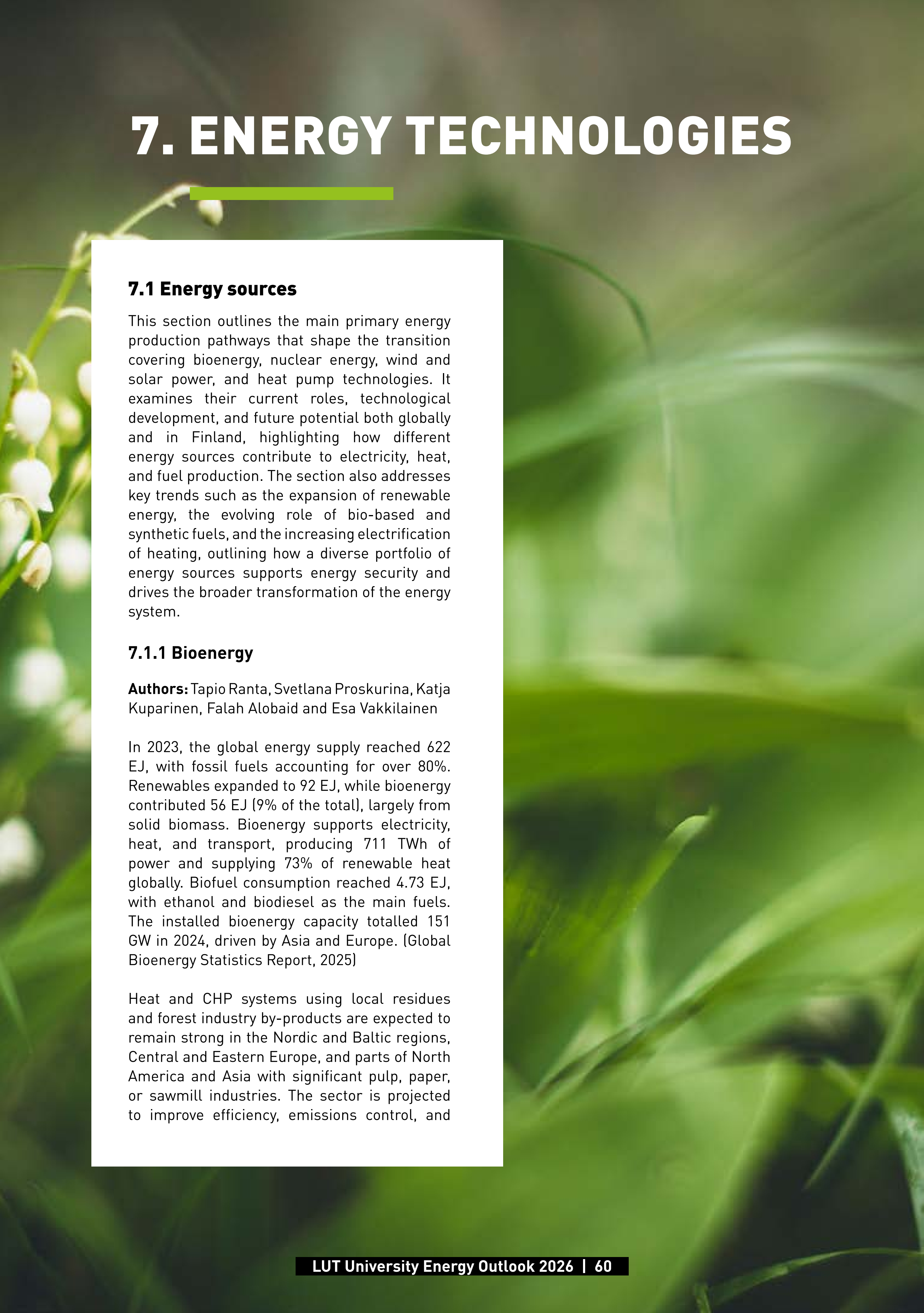


Figure 6.2 Competence profile of an individual team member, and the profile of a renewable energy "dream-team" (Paulomäki and Järvinen, 2025).

A transition to sustainable energy will require a highly skilled workforce. According to the IEA (2025d), on a global scale, about 36% of energy sector jobs are classified as high-skilled roles, typically requiring higher education such as a bachelor's degree or more. Another 51% fall into medium-skilled categories, which generally demand vocational or technical training—many of today's critical skill gaps, like those for electricians and welders, are in this group. Consequently, only around 13% of the energy workforce are considered low-skilled, performing mainly repetitive manual tasks (IEA, 2025d).

The energy as a field of study has maintained its appeal among young people and also adults looking for upskilling options (Vipunen, 2026). However, according to the estimates by the OPH, the number of highly educated people within the energy sector will be slightly lower than optimally needed in the near future. Finland's goal is to have 50% of young people entering university, but no progress has been made. The proportion of young adults (aged 25–34) with a higher education in Finland is 39 percent, which is below the OECD average (48 percent) (OPH, 2023).

Although a large share of global energy education is still largely focused on fossil industries, globally growing clean energy sectors are already drawing upon workers from fossil fuel sectors (IEA, 2025d). However, Finland needs to educate young people for the field since the options for sifting people from other fields are limited. A notable option for energy companies is to partner with educational institutions to design specialised curricula to meet industry needs. Public-private collaboration is essential to align education with evolving skill requirements (IEA, 2025d).



7. ENERGY TECHNOLOGIES

7.1 Energy sources

This section outlines the main primary energy production pathways that shape the transition covering bioenergy, nuclear energy, wind and solar power, and heat pump technologies. It examines their current roles, technological development, and future potential both globally and in Finland, highlighting how different energy sources contribute to electricity, heat, and fuel production. The section also addresses key trends such as the expansion of renewable energy, the evolving role of bio-based and synthetic fuels, and the increasing electrification of heating, outlining how a diverse portfolio of energy sources supports energy security and drives the broader transformation of the energy system.

7.1.1 Bioenergy

Authors: Tapio Ranta, Svetlana Proskurina, Katja Kuparinen, Falah Alobaid and Esa Vakkilainen

In 2023, the global energy supply reached 622 EJ, with fossil fuels accounting for over 80%. Renewables expanded to 92 EJ, while bioenergy contributed 56 EJ (9% of the total), largely from solid biomass. Bioenergy supports electricity, heat, and transport, producing 711 TWh of power and supplying 73% of renewable heat globally. Biofuel consumption reached 4.73 EJ, with ethanol and biodiesel as the main fuels. The installed bioenergy capacity totalled 151 GW in 2024, driven by Asia and Europe. (Global Bioenergy Statistics Report, 2025)

Heat and CHP systems using local residues and forest industry by-products are expected to remain strong in the Nordic and Baltic regions, Central and Eastern Europe, and parts of North America and Asia with significant pulp, paper, or sawmill industries. The sector is projected to improve efficiency, emissions control, and integration with heat networks, whereas large-scale, import-dependent biomass power plants may decline unless fitted with Carbon Capture and Storage (CCS) or Carbon Capture and Utilisation (CCU) technologies.

CCS and CCU are technologies designed to reduce CO_2 emissions from industrial processes and power generation. CCS involves capturing CO_2 and transporting it to secure geological storage sites, preventing its release into the atmosphere. CCU captures CO_2 for conversion into useful products, such as fuels, chemicals, or building materials. Over the past five years, CCS and CCU have seen gradual progress: several large-scale CCS projects became operational in North America, Europe, and the Middle East, improving the capture efficiency and reducing costs. CCU technologies have advanced more in pilot and demonstration stages, particularly in producing synthetic fuels and chemicals, but deployment remains limited compared to CCS due to economic and scalability challenges (IEA, 2026b).

Bioenergy with Carbon Capture and Storage (BECCS) is a technology that combines bioenergy production with carbon capture and storage to achieve negative emissions. In BECCS, CO_2 produced from biomass-based power generation, heat production, or industrial processes is captured and sequestered in geological formations, preventing its release into the atmosphere. Since biomass absorbs CO_2 during growth, BECCS can remove additional CO_2 from the atmosphere, making it a key tool for climate mitigation. Recent developments show that BECCS remains largely at the pilot and demonstration scale, with a few operational facilities globally. Additionally, the integration of biogenic CO_2 from sources such as biogas, ethanol, and biomass facilities with green hydrogen to produce e-fuels is attracting increasing attention, particularly for aviation and maritime applications. This approach is beginning to converge the boundaries between bioenergy and synthetic fuels.

Anaerobic digestion of manure, sewage sludge, food waste, and agro-industrial residues currently represents a small but rapidly expanding segment of global bioenergy, with notable growth in Europe, China, India, and North America (IEA, 2025e). The primary development involves upgrading biogas to biomethane for grid injection, transportation fuel, power-to-gas integration, or industrial feedstock. Biogas and biomethane are emerging as highly promising bioenergy solutions, particularly in agriculture-intensive regions due to their potential for methane mitigation and contribution to the circular economy.

Advanced thermochemical conversion technologies, including gasification, pyrolysis, and hydrothermal liquefaction (HTL), remain predominantly at demonstration or early commercial stages. Gasification and fast pyrolysis have reached higher levels of technology readiness, with several operational commercial plants globally, while HTL is progressing from pilot to early commercial deployment (IEA Bioenergy, 2023). Ongoing European and international projects are promoting integration and product upgrading for fuels and chemicals, indicating the gradual maturation of these technologies beyond purely experimental applications.

Liquid biofuels account for approximately 4–5 EJ of global final energy consumption, representing about 11% of total bioenergy use, and are predominantly utilised in road transport across the US, Brazil, and the EU (IEA, 2025a). Over the next 10 to 15 years, conventional biofuels are expected to remain significant, particularly where flex-fuel vehicles and high blending mandates persist, although long-term demand for gasoline and diesel blends is anticipated to stabilise or decline. Advanced biofuels including cellulosic ethanol, Fischer–Tropsch fuels, alcohol-to-jet, and HEFA derived from waste oils are projected to experience strong policy-driven growth through 2050. The sector is expected to shift focus from road transport toward aviation (SAF) and maritime applications, with advanced, non-food feedstock pathways gaining prominence due to the increasing adoption of SAF blending mandates and targets in many countries.

Finland ranks as the fifth-largest consumer of bioenergy in Europe, with one of the highest proportional shares of bioenergy in its national energy mix. In 2022, bioenergy accounted for 76% of the country's renewable energy production and 32% of its total final energy consumption (Bioenergy Association of Finland, 2026). Due to its low population density and extensive forest resources per capita, Finland has substantial domestic potential for solid biomass. Approximately 90% of its bioenergy is derived from solid biomass, mainly as by-products of the forest industry.

7.1.2 Nuclear energy

Authors: Heikki Suikkanen, Juhani Hyvärinen and Roosa Talala

Nuclear energy is a versatile, climate-friendly, and resource efficient energy source for multiple purposes and at various size-scales. Nuclear reactors produce heat, which can be used as such for residential or industrial heating purposes, or converted into electricity, motion, or energy carriers such as hydrogen. A few specialised reactors are also used to produce radioisotopes for industrial and medical uses. The heat output of a nuclear reactor ranges from 15 to 4,500 MW, whereas the electrical output can be 5–1,600 MWe. A nuclear power plant (NPP) can contain many reactors. There are over 400 power reactors in operation worldwide (IAEA, n.d.), and nuclear energy covers around 9% of global electricity production (IEA, 2025f).

Nuclear reactors have traditionally been designed for baseload electricity generation favouring a large unit size for improved economics; this trend has culminated in the deployment of the 1,600 MWe EPR design in Europe, now exemplified by its operation at the Olkiluoto power plant in Finland, its commissioning at Flamanville, France, and the construction of two reactors at Hinkley Point C in the UK. All these projects have experienced significant delays and cost overruns and as an alternative pathway to improved economics, small modular reactors (SMRs) leveraging mass production and faster deployment are being developed.

Significant new-build projects are being planned within Europe with aims to deploy both traditional large reactors as well as SMRs. Major examples include France with plans to build six EPR2 reactors (World Nuclear News, 2026a), Poland with three AP1000 reactors (World Nuclear News, 2026b), and Czechia with two APR1000 reactors (World Nuclear News, 2025a). Sweden also has announced significant nuclear new-build plans (World Nuclear News, 2026c). All these countries as well as some others are also actively planning to deploy SMRs, with France also actively developing European SMR technology, most notably the Nuward design (World Nuclear News, 2025b). Notable for the newbuild programs is that they come with some form of state support mechanism. In addition to deploying new nuclear capacity, lifetime extensions of current plants are another ongoing development with extensions being planned for 60% of the EU reactors. Especially in the United States, one important driver for increasing nuclear capacity are data centres, which need significant amounts of stable and reliable electricity. This is resulting in restarts of already shut down plants (World Nuclear News, 2024), as well as significant lifetime extensions of running plants.

With a 40% share of the electricity production in 2025 (Finnish Energy, n.d.), nuclear power is the single largest source of electricity in Finland, mainly providing a steady baseload generation, but today, with significant installed capacity of variable wind power in the energy system, also adjusting production when necessary. While the current political climate and the general opinion (Finnish Energy, 2026) are favourable towards nuclear power, construction of new nuclear capacity without support mechanisms is as seen challenging, as concluded in a recent study by Fortum (Fortum, 2025). This is the conclusion also in a study commissioned by the Ministry of Economic Affairs and Employment of Finland, in which lifetime extensions and power uprates of existing reactors are seen as the most profitable option, followed by SMRs for heat-only or cogeneration of heat and electricity (Finnish Government, 2026a). Like other countries with ageing fleets, lifetime extensions are being pursued in the ageing Finnish nuclear units as well, with the Loviisa power plant already granted an extension until 2050 (Fortum, n.d.) and lifetime extensions of Olkiluoto 1 and 2 being considered up to 2058 (Yle, 2025).

There is also new technological development in the nuclear field in Finland. The company Steady Energy is developing reactor technology dedicated to serving district heating networks with 50 MW-thermal reactor units. This development has progressed into the construction of a non-nuclear pilot plant to test the operational features of the design and establish supply chains (World Nuclear News, 2026d). Further innovations could arise by combining nuclear technology development with Finnish shipbuilding expertise to decarbonise maritime shipping with nuclear propulsion, as being proposed by the new Finnish startup SEATOM (SEATOM Technologies, n.d.). To reflect recent technological advances and new usage scenarios, Finland is updating its Nuclear Energy Act and safety regulations. The revised law is set to take effect in early 2027 (Finnish Government, 2026b).

7.1.3 Wind power

Authors: Katja Hynynen, Petteri Laaksonen and Olli Pyrhönen

Wind power has become one of the central technologies in the Finnish power system. During the past decade, the installed wind power capacity has increased rapidly, and wind power has become one of the largest sources of electricity production in Finland. At the end of 2025, a total of 158 new wind turbines with a capacity of 1,023 MW were installed in Finland. As a result, the total installed wind power capacity reached approximately 9,433 MW, resulting in 22 TWh annual energy production in 2025, which was 26.1% of Finland's electricity consumption.

Technological development has played a key role in enabling this rapid growth. Modern wind turbines have become significantly larger and more efficient than earlier generations. The rated power of onshore turbines installed in Finland has increased steadily, and new projects utilise turbines typically in the 6–8 MW range. Rotor diameters and tower heights have also increased considerably. In 2025, the average rotor diameter of installed turbines was close to 170 metres and the hub height approximately 160 metres. Larger rotors and higher towers allow turbines to access stronger and more stable winds above forested terrain, improving capacity factors and enabling economically viable wind power production all over Finland.

As the share of wind power increases, its weather-dependent nature increases the need for flexibility in the power system. Maintaining the balance between electricity production and consumption requires sufficient reserves and transmission capacity, flexible generation and consumption, as well as storage solutions.

One challenge relates to the geographical concentration of wind power production. A large share of Finnish installed wind power capacity is currently located in western and northern Finland, where wind conditions were more favourable for the first-generation commercial turbines and grid connection points were readily available. Finland is a large country and temporal variations in wind conditions are significant across the territory. The concentration of wind farms in limited areas leads to correlated fluctuations in wind power generation, increasing variability in nationwide production. A more geographically balanced distribution of wind farms would smooth national wind power generation, improve the overall system performance, and reduce price volatility in electricity markets.

Modern turbines have reduced regional differences in wind conditions by reaching higher altitudes, where wind resources are generally good across the country, enabling economically viable wind power production beyond the traditionally most favourable areas. However, wind power development in eastern Finland has so far remained limited due to restrictions caused by military radar surveillance. Several policy and technical solutions have been investigated in recent years to enable wind power investments also in eastern parts of the country.

In the future energy system, wind power is also expected to play a key role in the production of new energy carriers. Several large-scale projects in Finland are currently planning to combine wind power generation with hydrogen production through electrolysis. Such Power-to-X concepts can provide new flexibility in the electricity system by allowing part of the variable wind generation to be converted into hydrogen or other synthetic fuels. This can also improve the utilisation of renewable electricity in sectors that are difficult to electrify directly.

Another emerging development is the increasing integration of wind power with other renewable energy sources. Hybrid solutions that combine wind power with solar generation or hydrogen production can improve the utilisation of grid connections and smooth the overall power output of renewable energy plants. This development supports the evolution of wind power from a standalone electricity generation technology towards a more integrated and flexible energy system component.

7.1.4 Solar power

Authors: Altti Meriläinen, Leo Gardemeister and Antti Kosonen

The global cumulative capacity of solar electricity reached a full terawatt-peak for the first time in March 2022, and by the end of 2024 the capacity had already reached 2.2 TWp. The expansion of solar capacity has significantly influenced the cost of solar power systems: according to the mass-production learning curve, prices have historically declined by around 20% with each doubling of installed capacity since the 1970s, with this rate increasing to approximately 40% since the late 2000s, reflecting trends observed in semiconductor technologies (ITRPV, 2024). The technological development of solar modules has advanced considerably due to, among other things, rapid improvements in module efficiency. A mainstream module was producing 250 Wp in 2015, while in 2022 it was already 360 Wp, and in 2026 it reached around 450 Wp with the same surface area. The technological advancements of solar modules can be followed on the Clean Energy Review webpage. Advancements are also taking place in solar inverters, where new silicon carbide-based power electronics are being applied. Due to the increase in power density, a weight-to-power ratio of 0.25 kg/kW—roughly 100 times smaller than in solar inverters three decades ago—can already be achieved using a 400 kW solar inverter (PV Magazine, 2023).

Since 2019, the solar electricity capacity connected to the Finnish electricity grid initially increased by about 100 megawatts annually but started surging in 2022. According to the Energy Authority (2025), solar power production in Finland amounted to roughly 1,247 megawatt-peaks by the end of 2024, representing an increase of over 240 megawatts (24%) from 2023. At the end of 2025, the total installed capacity had reached 1,512 MW (Fingrid, n.d.). The share of solar power in Finnish electricity production has reached 1.4%, and this continues to grow. Fingrid (2023) estimates that Finland may have a solar electricity production capacity of seven gigawatt-peaks by 2030. However, Finland still has relatively little solar electricity production compared to leading European countries. For example, the per capita solar electricity capacity in the Netherlands at the end of 2022 was nine times that of Finland (IEA, 2022a). Even though solar electricity production capacity in Finland is still limited, the significant amount of solar electricity produced in Europe has also had ripple effects on the Finnish electricity market in the form of low-cost afternoon electricity. Therefore, in contrast to previous years, the price of afternoon electricity in Finland has been negative on several occasions. Excluding an extreme bidding error on Friday, 24th of November 2023, which caused the electricity price to drop below –500 euros per megawatt hour for ten hours straight, a record low was reached in Finland on Sunday 16 July 2023 between 15:00 and 16:00, when the tax-free wholesale electricity price dropped below –60 euros per megawatt hour (–6 cents/kWh). The Netherlands has even seen electricity prices of -400 euros per megawatt hour (PZEM, 2023).

More recent plans in Finland are to set up several individual solar farms with capacities of several hundred megawatts. In practice, these planned utility-scale plants will be located near the transmission network for cost efficiency reasons. The plants will be installed on ground mounted systems and will need land areas where construction is cost-efficient. Alongside traditional fixed tilt, single-axis tracking systems are becoming increasingly more common for these utility-scale projects. By continuously following the sun's trajectory, single-axis tracking can significantly increase the overall energy yield and capture more production during morning and evening hours when electricity prices are typically higher. According to Fasihi (2025) the investment cost of a single-axis tracking system is approximately 10% higher than fixed tilt systems with production increasing usually by 20–30%. Furthermore, production can be increased even further when equipped with bifacial modules, which exceeded 90% of the market share in 2025 (Keiner, 2025). Renting land for this purpose may bring municipalities and landowners significant rental income. As opposed to building-integrated photovoltaics, industrial projects have provoked extensive debate among nearby residents. The profitability of industrial plants meant solely for electricity production depends purely on the electricity market price, whereas that of building-integrated photovoltaics depends on the overall price of electricity. However, rising interest rates, inflation and declining electricity prices have reduced the motivation of many private citizens to install solar photovoltaic systems in 2023.

Safe and up-to-requirement installations have become a burning issue as the number of integrated systems has increased. The rapid growth in demand has led to a shortage of skilled installers. According to the Finnish Safety and Chemical Agency (2023), shortcomings or clear errors were found in a significant number of solar photovoltaic installations. Another noteworthy matter is the fire safety of the systems. For that purpose, the network of Finnish rescue departments has prepared separate fire safety guidelines (Pelastuslaitokset, 2023). A third issue to consider are the possible guidelines of insurance companies, which need to be taken into account in solar photovoltaic installations.

7.1.5 Heat pumps (and geothermal)

Authors: Antti Uusitalo and Teemu Turunen-Saaresti

Heat pumps have a significant role in electrifying heating, reducing fossil fuel use and lowering emissions. In 2022, the IEA estimated that heat pumps could reduce carbon dioxide emissions globally by at least 500 million tonnes by 2030 (IEA, 2022b). One major advantage of heat pump technology is their ability to utilise various types of low temperature heat sources, which are technically difficult or uneconomic to be harnessed with any other technology. Potential heat sources include ground heat, heat from outside air, and different low-grade waste heat streams. For this reason, the use of heat pumps also improves the utilisation of local energy sources as well as increases self-sufficiency and energy security by reducing the need for imported energy sources. In addition, one of the major advantages of heat pump technology is that it can be used for combined heating and cooling.

Heat pumps are already widely used in building heating. In 2021, heat pumps produced roughly 10% of the heating energy of buildings globally, but the number of heat pumps continues to increase strongly, replacing other forms of heating and energy sources (IEA, 2022b). For example, the role of heat pumps in the Nordic countries greatly surpasses the global level, showing the largest number of heat pump installations per household (EHPA, 2025). In Norway, about 60% of buildings have heat pumps, while in Finland and Sweden, the corresponding figure is over 40%. After a decade of heat pump market growth in Europe, hitting the record in sales in 2022, heat pump sales have recently slightly declined. In 2024 2.3 million heat pumps were sold in Europe, including market data from 16 EU countries, Norway, Switzerland and the UK (EHPA, 2025). In 2025, about 112,000 new heat pumps—the majority being air source, air-water, and geothermal heat pumps, were installed in Finland, showing around a 10 % increase when compared to the sales in 2024 (SULPU, 2026).

There has been constant development in both small- and large-scale heat pump technologies with the development focus areas including the use of more environmentally friendly refrigerants, improving system and component performances, as well as achieving improved energy saving through advanced control. Large fluctuations in electricity prices are also providing greater possibilities to utilise heat pumps in

demand response for electricity. Currently, there is a significant development and transition towards the use of natural refrigerants in heat pumps and refrigeration systems (e.g. carbon dioxide, ammonia, different hydrocarbons). This transition is supported by new restrictions and legislation concerning the use of synthetic refrigerants. The updated EU F-gas regulation entered into force in 2024 restricting and phasing out the use of high global warming potential fluorinated gases. In addition, a legislative process in the EU is currently ongoing, with the aim to set restrictions for a large number of fluorinated substances categorised as PFAS or substances producing PFAS as their breakdown products, including many widely used synthetic refrigerants.

There has also been a growing interest in utilising heat pumps in industrial processes and in other large-scale systems, such as in district heating networks. According to an estimate from 2016, heat pumps could profitably cover 75 TWh of the EU's industrial heat production, whereas the corresponding technical potential is much higher, estimated to be roughly 480 TWh (Wolf and Blesl, 2016). Heat pump technology has been developed continuously, and the current potential of heat pumps is likely to exceed this estimate. In the Nordic countries, there are already many examples of the use of large-scale heat pumps in district heating. In such systems, low grade heat sources such as water heat in treatment plants or waste heat from data centres or industrial processes are recovered, and the temperature is increased with heat pumps (80–100°C). Example facilities include the Katri Vala heat pump facility in Helsinki, producing 160 MW of heating and 100 MW of cooling for the district heating/cooling networks. Another example is a heat pump facility in Esbjerg, Denmark with a heating capacity of 50 MW and the system uses carbon dioxide as the refrigerant (MAN Energy Solutions, n.d.). Currently, one of the key technological developments in large-scale systems is to achieve greater temperature rises and higher supply temperatures. Modern commercial high-temperature heat pumps can already achieve temperatures of up to 120–150ºC, which enables producing hot water but also low-pressure steam for industrial processes (Wolf & Blesl, 2016). High temperature heat pumps combined with steam compression technology (MVR) could produce process steam at higher temperatures, with the potential to replace fossil fuel fired boilers in many industrial processes (Klute et al., 2024).

7.2 Energy solutions

This section goes through some of the key technological pathways required to decarbonise our energy system with a focus on hydrogen solutions, carbon management, energy storage, and energy efficiency. The section presents how low-emission hydrogen can support industrial transformation and enable new value chains, highlighting also the importance of carbon capture, utilisation, and removal in managing emissions across sectors. The section also provides an overview of the rapidly evolving energy storage technologies that are essential for balancing supply and demand, ensuring grid stability, and enabling the large-scale integration of renewable energy. It further emphasises the critical role of energy saving and efficiency measures in reducing the overall demand. These approaches demonstrate the opportunities and challenges involved in building a flexible, low-carbon, and secure society.

7.2.1 Hydrogen solutions

Authors: Tero Tynjälä and Pertti Kauranen

The role of low-emission hydrogen is expected to grow significantly in the future energy system. Hydrogen is not an energy source. It is an energy carrier, and, according to estimates, its direct use only accounts for a small part of total consumption. Other uses for hydrogen include different Power-to-X products—such as chemicals, plastics and adhesives—which are currently made from fossil oil or gas. Many of the current users of hydrogen, such as producers of biofuels, fertilisers and hydrogen peroxide, are planning to switch from grey (natural gas-based) hydrogen to green hydrogen. If it is mixed with natural gas or biogas, hydrogen can also be a substitute for natural gas in industrial heat production and electricity generation based on fuel cells or gas turbines. Gas turbines and internal combustion engines based on pure or nearly pure hydrogen combustion are also in the research and pilot stages. Fossil-free steel production by means of hydrogen reduction requires large amounts of hydrogen. For example, the steel factory in Raahe would need an electrolyser capacity of roughly 1 GW if it were to switch from coal to hydrogen produced by water electrolysis.

Low-emission hydrogen can be achieved via low-emission electricity (green hydrogen), biomass through gasification or fossil coal/gas combined with Carbon Capture and Storage (CCS) (blue hydrogen). Globally, there is strong political momentum for low-emission hydrogen production, but deployment is not taking off as rapidly as would be needed for 1.5°C scenarios.

In the IRENA 1.5°C Scenario, the global low emission hydrogen targets for 2030 and 2050 are 125 Mt and 523 Mt, respectively (IRENA, 2024b). The European Commission estimates that by 2030, Europe will need 500–550 TWh of new renewable electricity capacity to achieve the RePowerEU programme's target of 10 Mt of domestic green hydrogen production and another 10 Mt of renewable hydrogen imports (EC, 2022).

In Finland, hydrogen has so far mainly been produced from natural gas through steam reforming. The declining availability and rising price of natural gas have accelerated the transition to hydrogen production with water electrolysis. Electrolysis consumes a great deal of electricity (approx. 50 MWh/tH2), and clean hydrogen production requires reasonably priced, zero-carbon electricity.

Rapidly increasing wind power generation and a new nuclear power plant have improved the possibility of producing clean hydrogen in Finland. Fingrid has estimated that Finnish wind power production will reach 60 TWh in 2030, and the realistic production potential is many times greater (Fingrid, 2024b). Finland has the opportunity to become an important energy producer in the EU area, and increasing renewable energy is much simpler in Finland than in Central Europe, where a much greater share of the land area has been harnessed for wind and solar power production and electricity generation is still largely based on fossil coal and gas. If Finland produced 10% of the EU's 2030 target for renewable hydrogen production—in other words, one million tonnes of hydrogen—it would require about 50 TWh of electricity and about 8 GW of installed electrolyser capacity depending on operating hours and system efficiency. So far

Finland's largest green hydrogen production plant has been built by P2X Solutions in Harjavalta. Its electrolyser capacity is 20 MW, and it started operation in early 2025. An electrolyser capacity of 8 GW would require 400 equivalent investments by the end of the decade, which means that hydrogen technologies need to be scaled up quickly. P2X Solutions has plans to scale-up production capacity by building the next 40 MW plant in Joensuu and a 100 MW plant in Oulu. There are several green hydrogen investments in the planning phase but only few with confirmed investment decisions. The largest in planning are 1 GW plants designed for hydrogen production for ammonia and green steel production by PlugPower in Kokkola and Kristiinankaupunki.

In addition to hydrogen production, there is also a need to develop hydrogen storage and distribution infrastructures. Gasgrid has introduced plans to develop a Finnish national hydrogen network. Planning and evaluation of environmental impacts started in 2025 and after discussions with landowners the first routing plan is estimated to be ready in 2027. The first draft of the routing was published 2025 and the pipeline would follow the west coast from Tornio to Turku-Naantali region and further to south-coast Inkoo and Porvoo and possibly further to Eastern Finland.

Hydrogen is rarely used as is and future uses of hydrogen are mainly based on hydrogen derivatives such as methane and methanol, which are easier to store and transport. Methane and methanol in their current form are directly or nearly directly applicable to many internal combustion engines, and methanol seems to have the most potential for the decarbonisation of maritime transport. Hydrogen based e-methanol can also convert further to different fuels and chemicals, such as aviation fuel, gasoline and different plastics and other materials currently made from fossil raw materials. Chemical processes require often steady operation and to this end either hydrogen pipelines or hydrogen storage are needed to guarantee the uninterrupted supply of hydrogen to large scale chemical processes. Large scale underground caverns are often seen as the most economical future solution for hydrogen production in an increasingly varying operation environment.

In addition to hydrogen, chemical synthesis requires a carbon source. This could, for example, be derived from carbon dioxide separated from flue gases produced when using biomass, synthesis gas obtained from biomass by gasification, or carbon dioxide captured directly from the atmosphere. More information on the carbon cycle and its management is presented in the next section.

7.2.2 Carbon management

Authors: Hannu Karjunen and Tero Tynjälä

Carbon management refers to the set of technologies and practices used to reduce and control carbon dioxide emissions from human activity. These pathways may be based on natural processes or technological solutions. A common feature of these is that carbon itself is an active element of the process, distinguishing them from other mitigation measures such as improving energy efficiency and replacing fossil fuels with renewable energy sources.

Carbon management actions can be broadly divided into three main pathways: 1) capture CO_2 from emitting plants and permanently store it underground (CCS), 2) capture CO_2 and use it to substitute fossil-based carbon (CCU), and 3) carbon dioxide removal (CDR) technologies, where the aim is to remove already emitted CO_2 from the atmosphere and store it permanently (EC, 2024). The different pathways partly utilise the same technologies and infrastructures, but the climate impact may differ depending on the carbon source (fossil, biogenic, atmosphere) and use cases (short, long, permanent carbon removal from the carbon cycle).

In 2025, the global CO_2 capture capacity was 64 Mt per year, a 25 % increase from the previous year. The majority of this is associated with natural gas production. Current development projects are chiefly located in North America and Europe. The Brevik CCS facility in Norway was officially opened in June 2025, marking a significant step for CCS as the world's largest CO_2 capture facility integrated into a cement plant. Other notable European CO_2 capture projects are the Hafslund Oslo Celsio waste incineration plant, BECCS Stockholm power generation unit, and Net Zero Teesside Power in the UK. In Finland, CO_2 capture has been recently tested at the Metsä Group's pulp mill at Rauma using a mobile testing platform. Globally, there have been only a handful of other demonstrations using pulp mill flue gases, specifically in Canada, the US, and Japan.

Within Europe, one of the primary drivers for development is the Net-Zero Industry Act, which mandates that 50 million tons of CO_2 per year must be stored geologically by 2030. Additionally, the inclusion of the maritime sector in the EU ETS, alongside other revisions, influences the demand for both CCU and CCS. The adoption of the reformed ETS II will also include transport and buildings sectors in emissions trading in 2027 or 2028. A voluntary Carbon Removal Certification Framework (CRCF) and the delegated acts related to it describe the certification methodologies necessary for using technologies such as Bioenergy with Carbon Capture and Storage (BECCS), carbon farming, and carbon storage in products. However, the carbon certificates are not yet valid for use in the ETS, limiting the usefulness of the CRCF framework as of now.

The most important CDR technologies (technological carbon sinks) are bioenergy with carbon capture and storage (BECCS), direct air capture (DACCS), reforestation, and carbon sequestration in carbonates, wood products, soil, biocarbon, and other long-lasting materials.

7.2.3 Energy storage

Authors: Pertti Kauranen, Aki Grönman and Jukka Lassila

Electrical energy can be stored as mechanical, chemical, electromagnetic or heat energy. Energy storage has many uses, including consumer electronics, electric vehicles, industrial reserve capacity, electricity grid stabilisation, and renewable energy storage. The need for storage may be short-term, such as stabilising the grid for seconds or hours, or long-term, such as storing solar energy from day to night or seasonally from summer to winter. Two technologies, lithium-ion batteries and pumped hydro storage, dominate the electricity storage markets.

Lithium-ion battery development is driven by the automotive industry's need for electric vehicle batteries. The annual production of lithium-ion batteries has doubled to 2,000 GWh in just a few years and is expected to reach 4,000 GWh by 2030, which would meet the needs of 50 million electric vehicles annually. The amount of energy storage connected to the grid is estimated to remain at 10% of the electric vehicle battery market. The growth of the battery market is restricted mostly by the availability of raw materials and insufficient investments in raw material production. In addition to lithium-ion batteries, Chinese companies in particular are investing in sodium-ion (Na-ion) battery technology. Its performance is slightly lower, but the raw material base is wider. Na-ion battery technology is being scaled for mass production, and it is already emerging in the energy storage market, as well.

More than 100 GW of new battery energy storage systems (BESS) were installed globally in 2025, almost doubling the installed capacity to 267 GW and 610 GWh. BESS has overtaken the role of pumped hydro storage as the most important grid-scale energy storage technology. However, BESS represents a short-term storage technology for a few hours to stabilise the electricity grid, whereas PHS plants can store energy even for multiple days. Close to 200 GW of PHS plants are deployed globally but only 8 GW of new capacity was installed in

2025. Obstacles to their adoption include lack of suitable locations, cost and environmental issues. The City of Kemijärvi recently rejected a 550 MW pumped hydro plan by Kemijoki Ltd due to environmental concerns.

The role of other storage technologies, such as compressed air storage, gravity based mechanical storage, liquefaction- and cryogenics-based energy storage and vanadium flow batteries, is only marginal at this time. Lithium battery use is currently dimensioned based on a capacity of 0.5–4.0 hours, which enables battery systems to operate in the electricity grid's balancing energy and reserve markets, balance out consumption peaks, and function as a short-term energy storage and reserve power. Finland's largest battery energy storage, with an output of 90 MW, has been built adjacent to the Olkiluoto nuclear power plant to support the electricity grid when plant units are shut down or started up after a shutdown. Lithium batteries and ultracapacitors are deployed alongside hydropower in balancing capacity and reserve power markets, which reduces the maintenance needs of the hydropower plants.

Globally, lithium batteries meant for solar power storage typically have a four-hour capacity, which means they last from noon until the afternoon consumption peak. For seasonal storage, hydrogen and hydrogen based synthetic fuels are mainly suitable, but even that technology is still in its pilot stage and has relatively low round-trip efficiency. Figure 7.1 provides an overview of different storage technologies presented according to the storage capacity and discharge time.

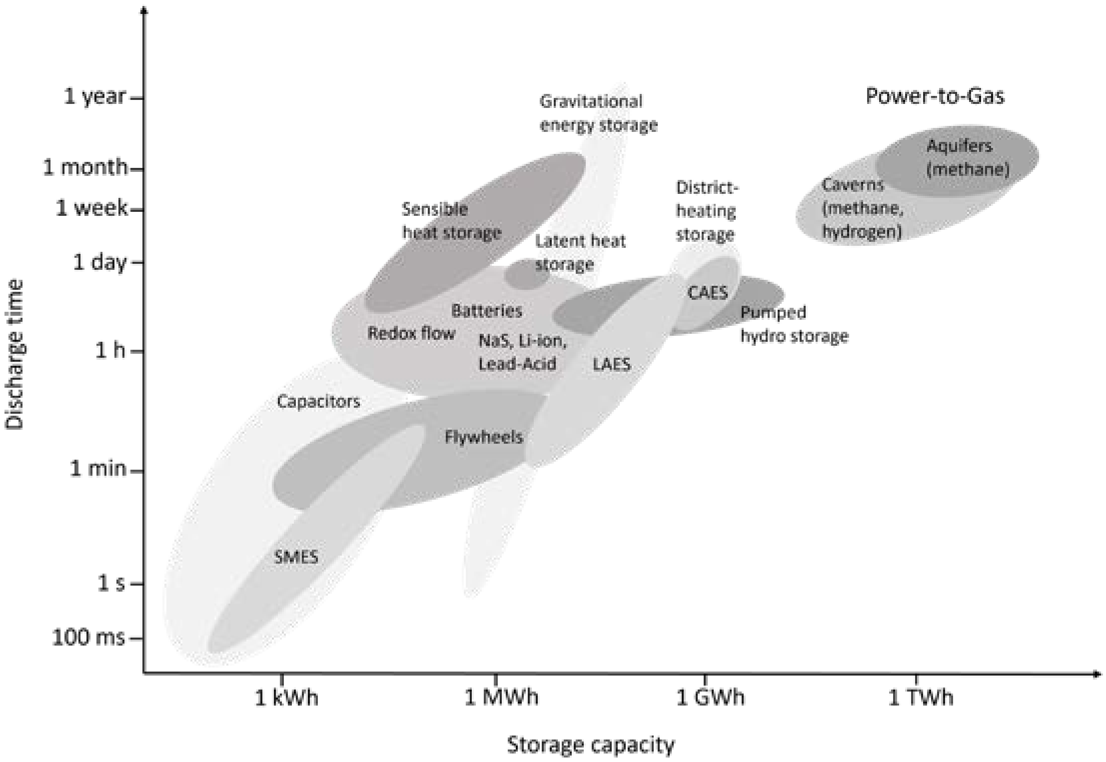


Figure 7.1. Energy storage according to capacity and storage life. The abbreviations in the figure are as follows: superconducting magnetic energy storage (SMES), liquid air energy storage (LAES), and compressed air energy storage (CAES).

The economics of energy storage depends on the acquisition cost but also essentially on the number of times it is recharged or discharged, which makes short-term storage systems more profitable. Seasonal storage systems with only a few recharging sessions per year are not financially viable in the current energy market. Many municipalities are now investing in seasonal hot water heat storage in rock caverns or steel accumulators, and its profitability is significantly influenced by fluctuations in the price of electricity.

If electric vehicles utilised bidirectional charging that would enable the battery pack to be discharged back into the electricity grid, this would provide significant reserve capacity for the grid. However, seizing that opportunity would require new technology both in cars and in charging stations, sufficient incentives for electric vehicle drivers, and improved battery durability to avoid the shortening of battery life spans due to increased use.

7.2.4 Energy saving and energy efficiency

Authors: Jero Ahola and Aki Grönman

Energian säästöllä tarkoitetaan toimenpiteitä, Energy saving refers to measures that reduce the use of services that consume energy, which can often be done without compromising the service experience of the energy consumer. Practical applications include smart controllable indoor lighting, room temperature control, or carbon dioxide-controlled ventilation. Energy efficiency, on the other hand, aims to reduce the amount of energy needed for energy services. As concepts, energy saving and energy efficiency do not take a stand on the overall amount of energy services produced. The total energy consumption may increase even if energy saving measures are implemented and energy efficiency improves.

The electrification and digitalisation of the energy system in general promote energy saving and energy efficiency. Due to electrification, energy efficiency will continue to improve especially in transportation, heating and lighting, where current technologies will be replaced with more energy-efficient alternatives. Examples include electric vehicles, heat pumps and LEDs. In industrial applications, increasing the use of pumps, blowers, fans and compressors controlled with frequency converters will continue to improve energy efficiency. Demand response has emerged alongside energy saving and energy efficiency. In an electrical energy system based especially on wind and solar power, the availability and cost of energy depend strongly on the prevailing weather conditions.

At the national level in Finland, energy saving and energy efficiency are controlled by the EU's energy efficiency directive, which Finland has implemented through its national energy efficiency act. A key tool in promoting energy efficiency and energy saving are the energy efficiency agreements concluded by industry and communities, which cover about 60% of the total energy consumption in Finland. In the agreements, organisations agree to report on and develop their energy saving mechanisms and energy efficiency, for example, in accordance with their own financial and environmental targets. At the Finnish national level, energy efficiency and energy saving are coordinated by Motiva, a state-owned sustainable development company.

The European Union sets common energy efficiency targets for its member states. The latest Energy Efficiency Directive (EU/2023/1791) more than doubles the annual energy savings obligation. Finland prepares its own legislation based on these targets (EC, 2023). Finland finalised its actions in the National Energy and Climate Plans, and submitted them to the European Commission in June 2024.

However, the EU EED has faced criticism—even directly from the Finnish Ministry of Trade and Industry. The sore points for Finland include not taking previous achievements or a northern location into account, fixing the final energy consumption, and a lack of legal options to promote energy efficiency.

Finland has long worked to promote energy efficiency, made large reductions in energy use and been the gold standard in the field. Finnish achievements have often surpassed the activities of many other nations. The EU does not take this into account and issues provisions that allow for 'the same increase despite the starting point'. A typical example is the fact that Finnish houses have been utilising triple-glazed windows for a long time. These are hard to improve upon, whereas many European countries are just starting the push for double-glazing. Achieving the same reduction in household energy use is more expensive in Finland. The mandate to achieve large energy efficiency gains in Finnish buildings is seen as particularly problematic.

The push to reuse or preserve old buildings does not help in reducing the overall building energy use. The situation with government and municipal buildings is particularly difficult. If the target is to construct buildings that last 100 years, rebuilding them every 20 years because of new energy efficiency rules is problematic. From the energy efficiency point of view, mandating a reduction in final energy use looks good. The EU has reduced its final energy use for a number of years now. In the long run, mandating a decrease in final energy

consumption means decreasing economic activities related to goods manufacturing in the EU and promoting imports. While switching from petrol to electric cars and improving insulation will reduce the final energy consumption, a hydrogen economy will not. Finland aims to make a large amount of eFuels using hydrogen generated from low-cost non-fossil electricity and captured biogenic carbon dioxide for export to other EU nations. This activity could add EUR 4,000–9,000 million to national trade by 2050. All this hydrogen economy activity, even if it is supported by EU funds, will increase the final energy consumption and cause Finland to fail in achieving the mandated reduction.

Industry is hesitant to invest in energy efficiency, as 2–3 years of payback time is typically required to make replacement investments feasible. Large energy efficiency gains can often be achieved with investments that have an industrial payback time of 5–9 years. It would be easy to greatly improve Finnish industrial energy efficiency by providing 30% subsidies for industrial investments, but this is prevented by current industrial policy. In contrast, a large subsidy to improve supermarket energy efficiency by installing solar panels on roofs is permitted.

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