UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

# Carbon Neutrality in the UNECE Region

## Technology Interplay under the Carbon Neutrality Concept


UNECE

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# Carbon Neutrality in the UNECE Region: Technology Interplay under the Carbon Neutrality Concept

UNITED NATIONS
GENEVA, 2022

This publication is issued in English and Russian.

## ACKNOWLEDGEMENTS

This document supports implementation of the project called “Enhancing understanding of the implications and opportunities of moving to carbon neutrality in the UNECE region across the power and energy intensive industries by 2050 – Carbon Neutrality project”.

This report was prepared by Walker Darke under strategic guidance and advice of Iva Brkic, Project Lead.

The project team thanks to Holger Rogner and Behnam Zakeri from the International Institute for Applied Systems Analysis (IIASA) for providing data analysis as well as the UNECE Task Force on Carbon Neutrality for the various comments and support through numerous consultations. The project team also wishes to thank Shuyue Li for providing visual communication and design services for this publication.

**Disclaimer**

# ABBREVIATIONS AND ACRONYMS

| Acronym | Expansion | Additional Information |
|---|---|---|
| AFOLU | Agriculture, Forestry, and Other Land Use | |
| BCM | Billion Cubic Meters | |
| BECCS | Biomass Energy with Carbon Capture and Storage | |
| CCUS | Carbon Capture, Use and Storage | |
| $CH_4$ | Methane | |
| $CO_2$ | Carbon dioxide | |
| CRL | Commercial Readiness Level | |
| COP26 | 26th UN Climate Change Conference of the Parties | |
| DAC | Direct Air Carbon Capture and Storage | |
| DH | District Heat | |
| EJ | Exajoule | 1018 joules Unit of Energy |
| EOR | Enhanced Oil Recovery | |
| GDP | Gross Domestic Product | |
| HELE | High-Efficiency, Low-Emissions | |
| LCA | Life Cycle Assessment | |
| $MTCO_2$ Eq. | Metric Tonnes of Carbon Dioxide equivalent | |
| MW | Megawatt | 106 W (watt) = 106 J/s, unit of power |
| NDCs | National Determined Contributions | |
| SMRs | Small Modular Reactors (Nuclear) | |
| SRL | Social Readiness Levels | |
| TRL | Technology Readiness Level | |
| UNECE | United Nations Economic Commission for Europe | |
| UNDP | United Nations Development Programme | |
| UNEP | United Nations Environment Programme | |
| UNFC | United Nations Framework Classification for Resources | |
| UNRMS | United Nations Resource Management System | |

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# FOREWORD

Alongside my team of experts, I attended the 26th UN Climate Change Conference of the Parties (COP26) in 2021 to meet with activists, diplomats, and Heads of State from the UNECE region and beyond to find common ground on a range of topics essential to delivering on the Paris Agreement targets and the 2030 Agenda for Sustainable Development. The compromise agreements at COP26 reflected the wide variety of interests, contradictions, and political will that we see today. This included sustainable energy. I am pleased to note that UNECE delivered real action to move the dial on sustainable energy, our Commitment Trifecta, and the Push to Pivot.

Energy is critical to supporting peace, cooperation, sustainability, and quality of life in our region. Experts have found clear pathways for policymakers to attain a carbon-neutral energy system. Energy efficiency improvements, renewable energy, high-efficiency fossil fuel technologies with carbon capture, use, and storage, nuclear power, hydrogen and integrated and sustainable management of natural resources are all part of the solution to attain carbon neutrality. However, only bold, immediate, and sustained action can decarbonize energy in time to avoid a climate disaster.

I remain convinced that international cooperation is essential to support all countries in the UNECE region to build resilient energy systems and accelerate the energy transition toward attaining carbon neutrality. UNECE continues to offer a platform for its member States to engage in inclusive and transparent dialogue, exchange best practices, and learn from each other to attain energy targets as part of the Sustainable Development Goals.

Inaction is a policy choice that will lead to greater, possibly insurmountable, challenges in the future. Policy actions are needed now to prepare society and build the necessary infrastructure to make the best use of our natural resources. The scale and complexity of these challenges are becoming more apparent every day, as is avoiding disastrous climate change and meeting the target of limiting global warming to 1.5°C.

This publication calls for ambitious and bold action from governments, the private sector and regulators. Development of technologies will require new regulatory frameworks to support immediate commercialization. Policy frameworks should also incorporate legally binding commitments for increased international technology transfer, harmonized standards, and definitions for 'green' hydrogen, energy efficiency, and conservation. All decisions should be assessed against existing and upcoming net-zero and climate neutrality targets, with all energy infrastructure built to be net-zero compliant. Integrating innovative energy technologies, alongside the transformation of energy markets and downstream industries, is a challenge and an opportunity.

The investment required to achieve a low-carbon economy will have its financial return and avoid the incalculable cost of economic, social, and human disruption due to a climate catastrophe.

Approximately 80% of the primary energy mix in the UNECE region is currently fossil fuel-based. Although different countries will support various technologies in diverse ways, we need to deliver sustainable energy to address climate change and ensure quality of life at a global level. In short: inaction is not a viable option. UNECE will continue to support all member States to take action to accelerate their transformation and share good practices in urban and rural developments, particularly cities, industry, buildings, and transport while delivering on the 2030 Agenda on Sustainable Development and the Paris Agreement targets.

Olga ALGAYEROVA

Executive Secretary of the United Nations
Economic Commission for Europe

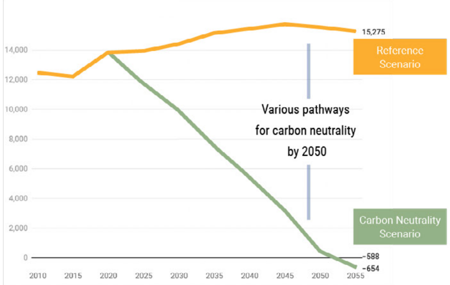
# EXECUTIVE SUMMARY

## LOW- AND ZERO-CARBON TECHNOLOGY INTERPLAY

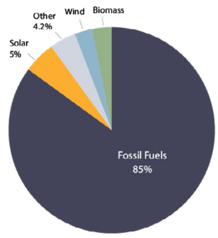
### The Roadmap to Carbon Neutrality by 2050 for Europe, North America and Central Asia

### How big is the gap to attain carbon neutrality in the UNECE region?

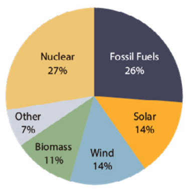
Climate models indicate that current national actions and international climate targets set in the Paris Agreement and COP26 fall short of delivering carbon neutrality and limiting global warming to 1.5–2°C.




Carbon Dioxide and Methane emissions in the UNECE Region [Mt $CO_2$eq]




**Reference** Scenario
Primary Energy Supply 2050

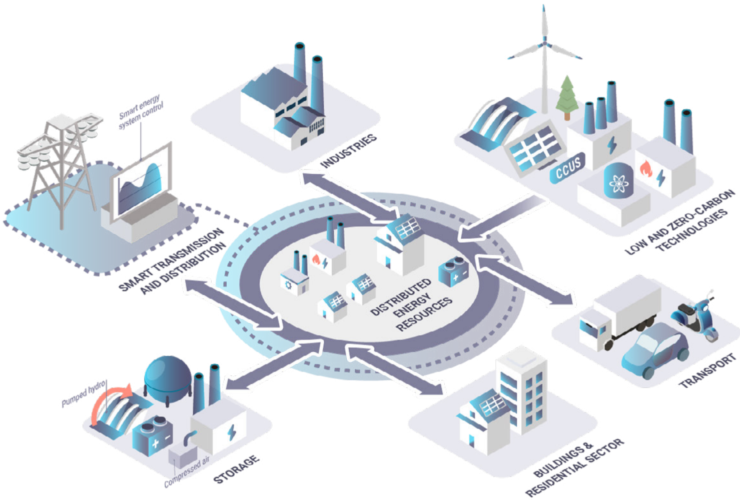



**Carbon Neutrality** Scenario
Primary Energy Supply 2050

There are achievable pathways for governments to design and implement a **carbon-neutral energy system** through **technology interplay** across sectors.

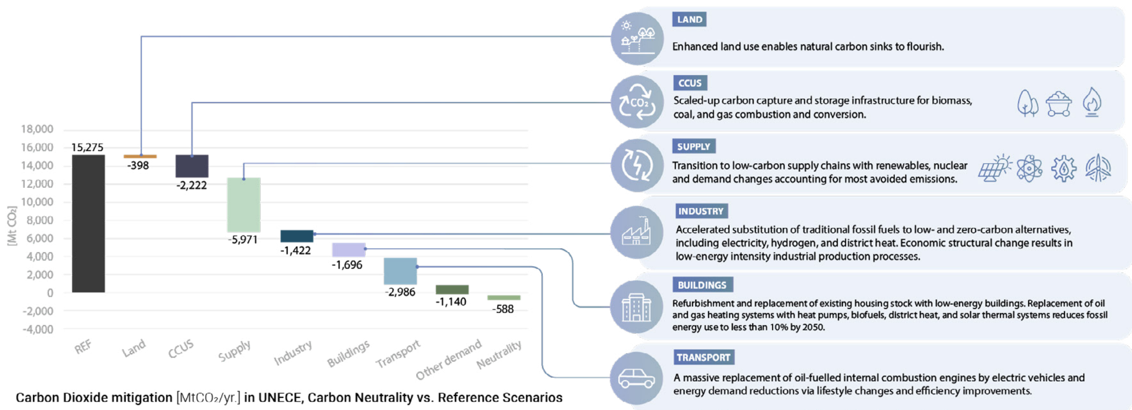
### Carbon-neutral energy systems require:

- **Diversifying** primary and final energy supply
- **Accelerating phase-out** of unabated fossil fuels
- **Electrifying** all sectors through renewable energy and nuclear power
- **Scaling-up innovative** low- and zero-carbon technologies




### How can different energy sectors be decarbonized?

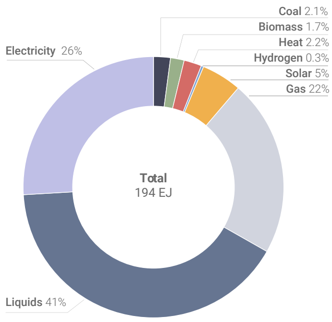
All low- and zero-carbon technologies are needed across sectors



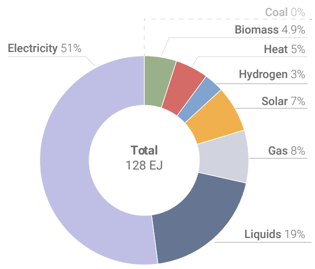

Carbon Dioxide mitigation [$MtCO_2$/yr.] in UNECE, Carbon Neutrality vs. Reference Scenarios

## What energy sources will be at the core of future energy systems?

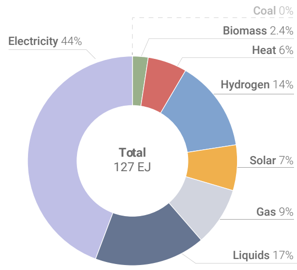
Diversifying and innovating resource base to attain resilient energy systems is the key




**Reference** Scenario
Final Energy Supply 2050




**Carbon Neutrality** Scenario
Final Energy Supply 2050

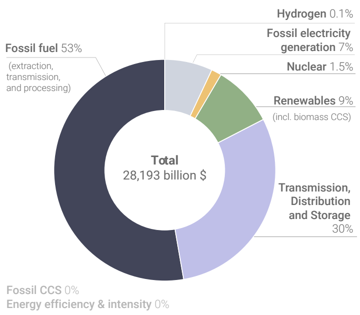



**Carbon Neutrality Innovation** Scenario
Final Energy Supply 2050

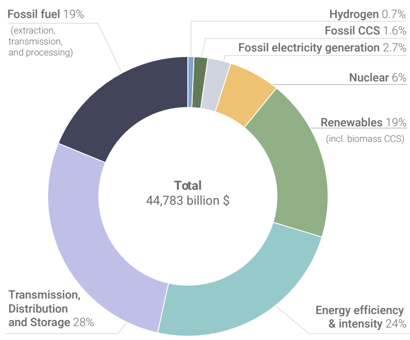
* **Reference Scenario** is based on historical trends and current policies.
* **Carbon Neutrality Scenario** reaches net-zero carbon emissions by 2050 and aims to limit temperature rises to less than 1.5°C by 2100.
* **Carbon Neutrality Innovation Scenario** accelerates market uptake of innovative technologies including carbon capture, use and storage (CCUS), nuclear power (large- and small modular reactor designs), and hydrogen.

## How much will the transition to net-zero cost?

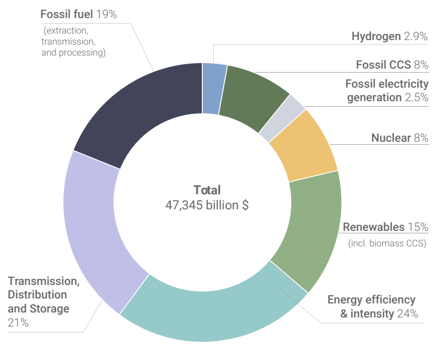
The cost to transition to carbon neutral energy systems is much lower than perceived. The cost of inaction is far greater as vulnerable energy systems are susceptible to the environmental, economic, and social consequences of climate change.




**Reference** Scenario
Total Investment needs 2050




**Carbon Neutrality** Scenario
Total Investment needs 2050




**Carbon Neutrality Innovation** Scenario
Total Investment needs 2050

## The UNECE region must accelerate:

- Technology transfer and deployment
- Institutional capacity to plan and drive the energy transition
- Buy-in and adoption from all stakeholders to build **secure, affordable, and resilient carbon neutral energy systems**
- Coordinated **international cooperation**

**The United Nations Economic Commission for Europe provides a much-needed platform for developing rules, standards, and norms for systemic lifestyle and infrastructural changes. UNECE has developed clear pathways for policymakers to attain a carbon-neutral energy system. International experts from all 56-member states have contributed to this work.**

## Objectives

This publication builds on the recommendations from the Pathways to Sustainable Energy Project and the UNECE Carbon Neutrality Project.

The publication builds upon a series of technology briefs that directly support the implementation of the Carbon Neutrality Project. The underlying objectives of this publication are to:

- **Inform policymakers about a range of options** and solutions to attain carbon neutrality
- **Support countries' efforts to reach carbon neutrality** and attract investments into clean infrastructure projects
- **Build capacity in economies** across the UNECE region to reach common goals

## Key Takeaways

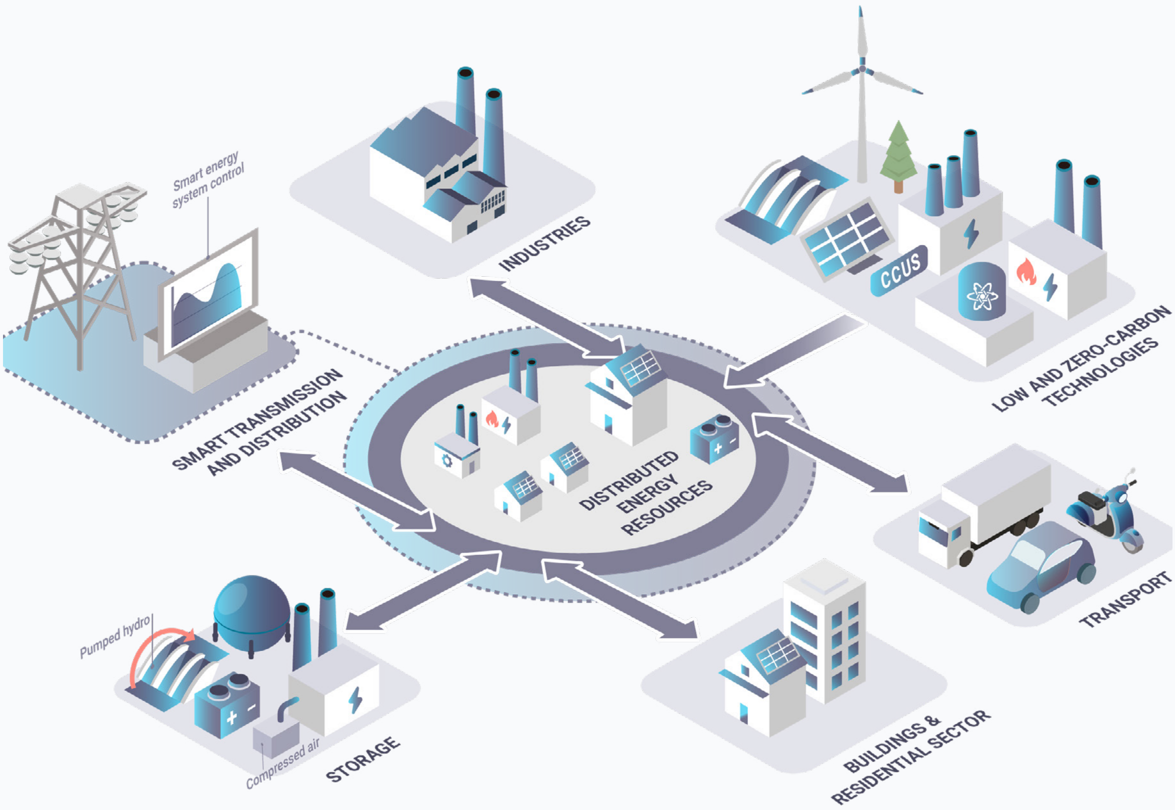
- **Problem**
  Climate models indicate that current national actions and international climate targets set in the Paris Agreement and at COP26 fall short of delivering on carbon neutrality and limiting global warming to 1.5–2 °C.
- **Mission possible**
  There are achievable pathways for governments to design and achieve carbon-neutral energy systems through technology interplay of all low- and zero-carbon technologies.
- **Technology interplay**
  Carbon-neutral energy systems consist of: I) the diversification of primary and final energy supply; II) an accelerated phase-out of unabated fossil fuels; III) the electrification of all sectors through renewable energy and nuclear power; IV) the widespread innovation of low- and zero-carbon technologies (incl. CCUS, hydrogen and advanced nuclear power, energy storage solutions).
- **Implications for the UNECE region**
  The UNECE region must increase: I) technology transfer and deployment; II) institutional capacity to plan and drive ambitious transformation of energy systems; III) buy-in and adoption from all stakeholders to build secure, affordable, and carbon-neutral energy systems.
- **Immediate Actions**
  Action must start now to maximize the use of all low- and zero-carbon technologies to achieve carbon neutrality by 2050. Governments need to: I) raise awareness about the merits of all low- and zero-carbon technologies; II) develop policy frameworks in support of carbon neutrality; III) create a level-playing field to finance a just transition toward carbon-neutral energy systems aligned to the needs of member States.
- **Role of UNECE**
  Coordinated international cooperation will be essential to attain carbon-neutral energy systems. UNECE provides a much-needed inclusive and neutral platform for developing rules, standards, and norms for systemic lifestyle and infrastructural changes. Supportive policies, incentives, and regulatory frameworks encourage regional and sub-regional technical cooperation across power, industry, buildings, and transport sectors for projects of common interest and public-private partnerships.

## The future carbon neutral energy system

Policymakers have clear pathways to attain carbon-neutral energy systems by combining existing and new technologies within integrated energy systems. All low- and zero-carbon technologies will play a role in interconnected systems where no energy system will exist in isolation. Innovation and digitalization enable energy systems that are efficient, resilient, and capable of delivering a net-zero region.

FIGURE 1

**Carbon Neutral Energy System of the Future**



# INTRODUCTION

As the recent Intergovernmental Panel on Climate Change (IPCC) report confirms, it is unequivocal that human influence has warmed the atmosphere, ocean, and land. It is now or never if we want to limit global warming to 1.5°C; it will be impossible without immediate and deep emissions reductions across all sectors. Climate change leads to extreme weather and subsequent social and economic disruption in every region of the world. At the same time, sustainable energy systems are critical for assuring quality of life and it underpins the attainment of the 2030 Agenda for Sustainable Development (2030 Agenda).

Climate models indicate that the current carbon emission reduction policies and National Determined Contributions (NDCs) fall short of what is required to meet the goal of limiting global warming to 1.5–2°C. There is a disconnect between countries' agreed energy and climate targets per the Paris Agreement and the actual progress made. We are running out of time to limit the impacts of climate change.

Inaction is a policy choice that could lead to more significant, potentially insurmountable, challenges in the future. Complex global energy systems are at the heart of all economies. On the supply side, national energy systems are not isolated but are part of optimized interconnected intra- and inter-regional systems. These systems are characterized by natural resources and technologies that can impact sustainable growth. A changing technology landscape driven by low-cost technologies as well as environmental and geopolitical concerns that significantly affect energy system design and policy options. Once energy systems start to change, downstream industrial users and consumers will need considerable time to adjust their activities to new energy systems.

Clean and low-cost energy technologies are growing quickly, but most are still at an early deployment stage. While technology options exist for most states, prohibitive costs, regulatory barriers, and social pressures prohibit large-scale deployment.

On the supply side, there are innovative ways to produce low- and zero-carbon energy, including renewable energy technologies, hydrogen, fossil fuels with carbon capture, use and storage (CCUS), and nuclear power. The multiplicity of choices makes it also imperative that there should be an integrated approach toward deciding on the optimum mix of technologies. The demand side has also experienced some decarbonization through system efficiency, electrification of the energy system, and digitalization. Innovative measures in industry, transport and buildings play a pivotal role.

2021 provided much-needed impetus toward carbon neutrality amid increasingly urgent calls for action. In September 2021, the UN High-level Dialogue on Energy convened the first global gathering on energy under the auspices of the General Assembly since 1981. It was the United Nations Year of Global Energy Action, and the UN Framework Convention on Climate Change held its 26th Conference of the Parties (COP26). At COP26, the final agreement:

> *Calls upon Parties to accelerate the development, deployment, and dissemination of technologies, and the adoption of policies, to transition towards low-emission energy systems, including by rapidly scaling up the deployment of clean power generation and energy efficiency measures, including accelerating efforts toward the phasedown of unabated coal power and phase-out of inefficient fossil fuel subsidies, while providing targeted support to the poorest and most vulnerable in line with national circumstances and recognizing the need for help towards a just transition.*

This report presents an analysis based on modelling results and explores various pathways for policymakers to attain carbon neutrality through technology interplay and to implement the 2030 Agenda. It needs to be noted that the modelling exercise conducted for the purposes of this report assumed that all technologies deliver decarbonization in time and in full. If the technology development and deployment are delayed in any way, or if a technology is removed from an agenda, the forecast for achieving carbon neutrality will need to be revisited.

The changing energy technology landscape impacts UNECE energy systems. The pathways to attain carbon neutrality are compatible with national interests. Nonetheless, policymakers must urgently finalize their current pathways and adapt their energy systems to comply with the Paris Agreement targets. The transformation of energy systems needs to start now and cannot be done in isolation.

## Defining carbon neutrality

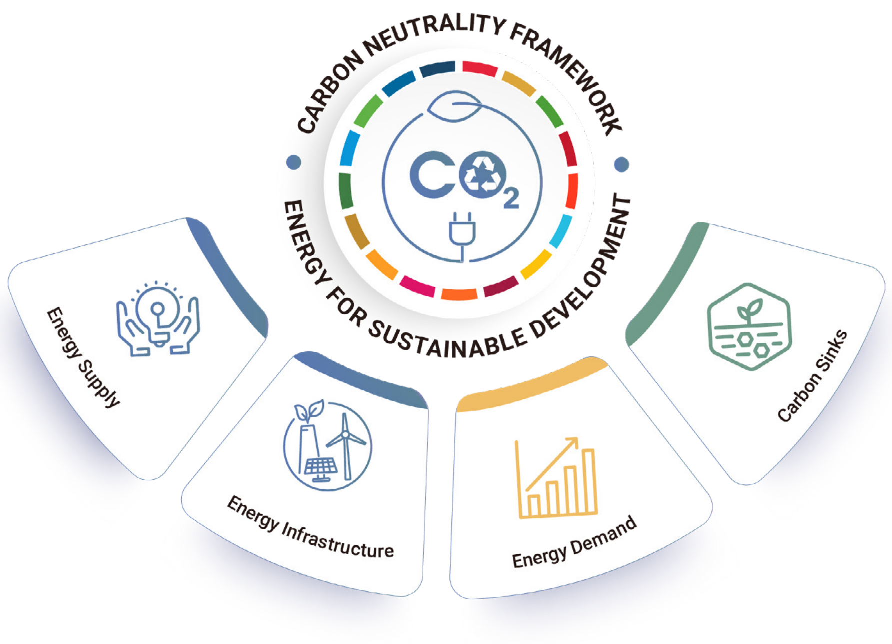
**Carbon Neutrality refers to achieving net-zero carbon emissions** with a goal of constraining global warming to 2°C (striving to 1.5°C) in line with the Paris Agreement. Carbon neutrality requires a careful balancing of actual carbon emissions with carbon removal through natural sinks, engineered carbon removal technologies and eliminating carbon emissions.

According to the Paris Agreement, carbon neutrality is defined as achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gas emissions in the second half of this century. In the context of this project, Carbon Neutrality refers to 'achieving net-zero carbon emissions that constrain global warming to 1.5–2°C by balancing reported carbon emissions (mainly carbon dioxide and methane) with carbon removal through natural sinks or engineered carbon removal technologies, such as CCUS, bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC), and by eliminating carbon emissions through a transition to a post-carbon economy.

**Carbon neutrality is not an end state.** It is an essential part of the journey to stabilizing the concentration of greenhouse gases in the climate. As a standalone policy target, however, carbon neutrality will not be enough to limit global warming. If carbon neutrality is achieved too late, net-negative carbon emissions will be required to address the overshoot. In the future, it is hoped that attaining carbon neutrality will enable the managing of carbon emissions over time and will need to be periodically revisited and address issues such as historical emissions.

FIGURE 2

**Carbon Neutrality Framework**



## Building resilient energy systems based on the sustainable energy and carbon neutrality frameworks

**Resilient energy systems based on the three pillars of energy security, quality of life, and environmental sustainability would protect society from future risks.** Energy security relates to securing the energy needed for economic development; quality of life refers to the provision of affordable energy available to all at all times; and environmental sustainability refers to limiting the impact of energy systems on climate, ecosystems, and health. The rapid transition toward sustainable energy will require careful decision-making to find the balance between all three pillars to deliver to the universally agreed 2030 Agenda for Sustainable Development.

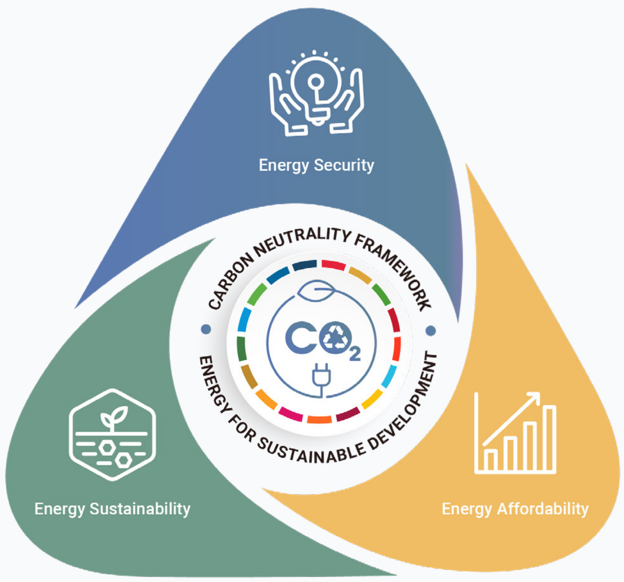
**Sustainable energy and carbon neutrality frameworks are essential for analyzing technology interplay.** The modelling and expert comments assume that the pace of economic development in each member state of the UNECE will be maintained and that each country will have its energy preferences and transition pathways based on its natural resource endowments, technological and infrastructure base, cultural heritage, historical patterns of economic development, and legal and regulatory structure.

**A commitment to ensuring access to affordable, reliable, sustainable, and modern energy for all** is included in the United Nations Sustainable Development Goals (SDGs). This approach embraces the SDGs and highlights the interconnectivity among the different facets of sustainable energy and trade-offs between the three pillars.

**Finding a balance between the three pillars is a complex social, political, economic, and technological challenge.** A dialogue under the UNECE Committee on Sustainable Energy would constitute a significant step for nations to identify trade-offs and synergies to deliver on energy security, quality of life, and environmental sustainability. While there are no easy answers, there is an urgent need to find a balance between those competing yet interrelated interests.

**FIGURE 3**

**The Energy Trilemma as a Framework to attain Carbon Neutrality**



## How is carbon neutrality achievable and why are innovative technologies needed?

Reaching consensus on the energy transition towards carbon neutrality is a complex problem. Policy choices have effects on existing and new energy technologies and economic growth, and they are subject to the availability of national energy resources. Increasingly tight timescales mean that ideal pathways to carbon neutrality are increasingly less feasible without imposing disruption to society. As each country has unique circumstances, equitable access to resources must be developed to attain carbon neutrality.

Adaptability in such a complex transition is vital to develop mechanisms to drive consensus amongst interested parties on ensuring timely, rapid decision making. A rapid transition is likely to disrupt society unless policymakers use all the available options. Even undesirable options may be necessary.

Carbon neutrality is achievable by using a mixture of low- and zero-carbon technologies and changes in social behavior. Energy demand will be driven by economic activity, lifestyle changes and improvements in energy efficiency, low-carbon fuels, smart technologies, and the electrification of all sectors. UNECE supports an integrated approach to energy technologies to represent all member countries' interests and maximize the synergies of diverse energy sources.

Across the UNECE region, fossil fuels currently dominate the energy supply due to legacy infrastructure, ease of transportation, storage, infrastructure, and energy density. Existing and new alternative low- and zero-carbon technologies need to be used to support sustainable development. Sustainable innovative solutions, such as CCUS, hydrogen and the advanced nuclear power, must be scaled-up to match traditional technologies' cost and technical competitiveness through technological advances, economies of scale, and closer alignment with market demand.

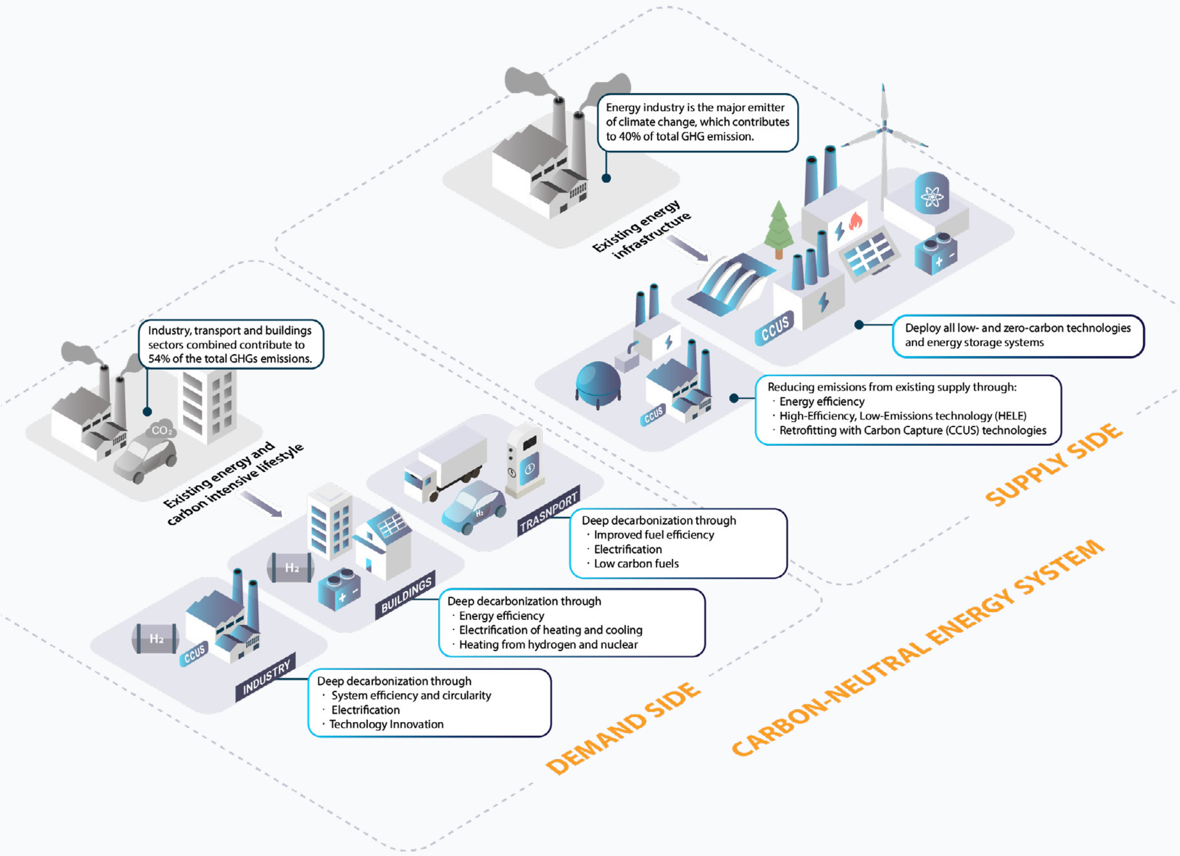
This report presents the analysis based on modelling results and shows an expanded set of technical options available to support policymaking and international energy cooperation. The solutions and technologies analyzed include energy efficiency, renewable energy, fossil fuels, nuclear power and hydrogen, and carbon sequestration approaches such as CCUS, BECCS, and direct air capture.

Policymakers should use Life Cycle Assessment (LCA) studies to validate their approach. LCA compares technologies on the basis of lifetime environmental impact from those with the lowest carbon footprint to those that require significant carbon capture and storage to be carbon neutral. It is almost certain that all low- and zero-carbon technologies will be needed during the transition. For example, policymakers can move to a hydrogen economy at the rate at which electrolyzers use low-carbon electricity from wind and solar energy as well as nuclear power. They can also decouple investments by using hydrogen from natural gas with CCUS to accelerate a hydrogen ecosystem infrastructure. Battery storage and improved management of distributed resources can stabilize and optimize grid electricity. Fossil fuels with CCUS and nuclear power as dispatchable energy sources can act as baseload and provide flexibility to intermittent renewable energy sources, such as wind and solar, and ensure the reliability of an energy system.

## To-do list for policymakers to attain carbon neutrality

FIGURE 4

**Actions to Attain a Carbon-Neutral Energy System**




To attain a carbon neutral energy system, the region needs to quickly deploy all currently available low- and zero-carbon technologies for energy supply as well as enhance system efficiencies. This includes transforming the energy supply by installing CCUS technologies in fossil fuel plants, scaling up renewable energy projects, deploying nuclear power, jumpstarting large-scale sustainable hydrogen projects, and deploying all other technologies considered in this review. In addition, national grids and interconnections will have to be enhanced and increased accordingly with the mix of energy supply and transnational equilibrium requirements. An expanded range of technologies is needed to attain carbon neutrality by 2050 and the 2030 Agenda. All energy technologies have disadvantages that can be minimized if used together and strategically.

Energy experts are aware that energy is a highly regulated sector and that any technology development and deployment require suitable regulatory frameworks. However, the modelling in this project does not factor the time required to implement regulatory changes. Developing technologies will need new regulatory frameworks to support immediate commercialization consistent with the energy market design and technical stability of the energy system. The urgency of the energy transition requires policymakers' coordination to ensure that the regulatory delays do not compromise the early attainment of carbon neutrality. The idea of a Social Readiness Level aligns policymakers with Technology and Commercial

Readiness Levels[1] used by experts. Policymakers should use these Readiness Levels when interpreting the modelling results as this indicates a likelihood that the decarbonization pathway is achievable.

Carbon neutrality will, ultimately, need significant changes to the way economies work, with potentially many unforeseen consequences. Any rapid introduction of change requires coordination of technology development, commercialization, and social acceptance. 'Readiness Levels' are a commonly used indicator of describing what needs to be addressed during the introduction of a change

Energy infrastructure built now must be net-zero compliant to avoid stranded assets. All infrastructure-scale assets have operational lives of more than 30 years. Therefore, any assets built now must be consistent with national emissions targets or easily retrofitted in the future.

Given the timescale and nature of this transition, modelling indicates that very large scale CCUS is required for many years. It functions as a last resort if the transition is delayed. It allows hard-to-abate essential industries such as cement, steel, and chemicals to continue and even when carbon neutrality is achieved, further extraction of GHG emissions may be needed. As the rate required for decarbonization is now so fast, CCUS could extend the operational lives of non-compliant infrastructure, provide a cap to excessive transition costs and avoid social disruption.

Energy efficiency and optimization will become at the core of all energy policymaking. It is an important element of energy demand management in a n¬et-zero 2050 world. This will require rapid deployment of efficiency measures and establishing optimal buildings, industry, and transport demand. Policy measures will include significant investment and workforce training to implement the monumental task.

Policies should encourage rather than delay changes in the energy system. Modelling under the Pathways to Sustainable Energy Project showed that progress has been too slow, and to attain carbon neutrality on route to the 1.5-2°C target, the UNECE countries must either additionally cut or capture at least 90Gt of $CO_2$ by 2050 in a 'middle of the road' socio-economic forecast[2]. 90Gt is equivalent to four years of current global $CO_2$ emissions. Policies are needed to decrease and optimize energy demand, decarbonize the energy supply, and deploy engineered and natural carbon removal technologies.

Life cycle assessment studies show that there is not a completely carbon-neutral energy solution. All technologies require materials and high-temperature processes that result in GHG emissions. Renewable energy solutions require steel, cement, and silicon. Electric vehicles and grids require rare earth metals in batteries. Hydrogen could leak into the atmosphere and have a negative impact. Energy investments may mean increased emissions today that will save emissions in the future. The modelling does not require an account for this shift in perspective, energy and GHG emission patterns in the economy because it is modelled using historical trends.

1 UNECE CCUS Technology Interplay, Technology readiness levels (TRLs) are a method for estimating the maturity of technology. Commercial readiness levels (CRLs) are a method that assesses various indicators which influence the commercial and market conditions beyond just the technology maturity. Social readiness levels (SRLs) are a method that assesses to what extent new ideas and innovations resonate with individuals and groups and whether they will be integrated into society and reach decisions concerning their adoption in the form of a regulatory and financial regime.

2 UNECE Pathways to Sustainable Energy, A reference scenario enables analysis of whether the world is likely to achieve specific goals along its current trajectory. This is a vital part of all research. Analysis of specific metrics based on the outcomes of a reference scenario may show that a long-term performance goal (LPG), such as a 25% reduction in energy intensity by 2050, would likely be achieved with our current assumptions about the pace of economic development and the evolving relationships between energy and economic development. The outcomes of a reference scenario may also show that, under the current set of assumptions and relationships, a specific LPG is unlikely to be attained. The reference scenario for the Pathways project is the Shared-Socio-Economic Pathway 2 (SSP2) (see section 2.3.), a "Middle of the Road" Pathway.

# Energy technologies modelled and analyzed

**Wind** power is a renewable energy source that uses turbines to convert wind onshore and offshore to electricity.

**Solar** power is a renewable energy source that uses sunlight through photo-voltaic cells (PV) or a set of mirrors and lenses to concentrate a large area of sunlight onto a receiver (concentrated solar power) to create electricity.

**Hydropower** is a renewable energy source that covers a wide array of technologies harnessing the forces of the natural water cycle.

**Geothermal** is a renewable energy source produced from heat inside the earth's crust. It can be used to generate electricity or used as a direct heat source.

**Biomass** is a renewable energy source made from biological source materials, which can include solid biomass, sewage biomass, forest residues, algae and agricultural wastes.

**Nuclear** power plants convert atomic energy into usable power. Conventional nuclear power plants produce heat to drive a turbine for electricity generation. Nuclear plants can provide heat for urban district heating and industrial processes.

**Natural Gas** is a fossil fuel commonly burned to produce heat to operate a steam turbine. It also has other uses in heat, cooking, industries, transport.

**Coal** is a solid fossil fuel commonly burned to operate a steam turbine to generate electricity and heat.

**Carbon Capture, Use and Storage (CCUS)** is the process of capturing carbon dioxide ($CO_2$) emissions from fossil power generation and industrial processes for storage deep underground or re-use. This technology can be combined with coal, natural gas and biomass.

**Hydrogen** is a bulk chemical that is used primarily today in petroleum refining and in the production of ammonia (for fertilisers) and methanol. In the future, hydrogen could be used as an energy carrier and energy storage medium.

**Electricity** and the process of making the energy system electric through electrification is seen as key to the rapid rollout of renewable energy sources.

**Electricity Storage** is the capture of energy to use later and includes lithium-ion batteries, dispatchable-hydrogen assets, and pumped-storage hydropower. In future, long duration energy storage could include developments in mechanical, thermal, electrochemical, and chemical storage.

**Energy efficiency** aims to use less energy to provide the same useful output for required energy needs.

## Modelling of scenarios: a tool for informed decision-making

**Technology interplay is critical for energy system transformation.** Interplay is key to balancing energy supply and demand with economic feasibility and sustainability. Technology chains link energy supply from resource extraction, conversion, storage, transmission, and distribution to the provision of energy services. Quantitative modelling of these chains helps identify the combination of technologies that form the lowest-cost supply and investment schedules while meeting energy security requirements and climate goals.

**Modelling of scenarios allows policymakers to see climate policy implications for emissions, energy costs, supply security, storage, and constant supply requirements versus variable supply requirements.** Policymakers can use modelling to identify technology and performance deficiencies and decide which technologies to support by understanding investment costs, lead times, and benefits and risks. The early engagement of policymakers in modelling exercises is essential to enable informed, agile, and responsive policymaking to attain carbon neutrality. Policy agility and flexibility will be needed to change paths if technologies currently under development do not meet expectations. Trade-offs will need to be made between different technology options, costs, pathways, energy security, and environmental protection.

**Modelling necessarily entails numerous assumptions about various future developments.** These include intertemporal dynamics, technology availability and performance, socio-political preferences, constraints, and boundaries. These assumptions will shape the findings as modelers form scenarios. Future scenarios are based on transparent assumptions about future developments affecting all relevant aspects of the energy system. Analysts and planners face challenges in quantifying parameters and variables, especially when different stakeholders have different views on the challenges, development dynamics, or desired outcomes. These assumptions aim to include various factors such as technical, commercial and social readiness levels of various technologies but may not fully capture uncertainties in the pathways, and such technologies are not available on time and at expected cost.

**For the purposes of this project, a modelling framework for medium- to long-term energy system planning, energy policy analysis, and scenario development was applied – the MESSAGE model**[3]. This modelling framework uses the lowest system cost to optimize energy systems under various technology and policy scenarios to attain carbon neutrality by 2050. Policymakers may wish to use additional criteria reflecting local and national conditions, capabilities, and ambitions for their energy system. This could include a preference for local resources, maximizing energy security, social welfare, and intergenerational equity.

**The scenarios modelled in the context of this project represent energy system transformation, technology interplay, and climate mitigation in a geopolitically stable world.** A common pitfall is using scenarios for analyses for which they were not designed. Major geopolitical disruptions, therefore, require not only separate scenarios and sensitivity tests but also significant revisions to the energy system model. The UNECE Carbon Neutrality scenarios explore plausible internally consistent development trajectories to 2050.

**Modelling uses a simplified representation of real-life energy systems.** This modelling aggregates geographical areas, economic sectors, and technologies to form judgments on required future technologies, lifestyle changes, and socio-political acceptance. Naturally, quantification involves assumptions under uncertainty. As the future is unknown, modelling must not be a single project, but an ongoing process based on the emergence of new insights.

3 IIASA MESSAGE Model provides a flexible framework for the comprehensive assessment of major energy challenges and has been applied extensively for the development of energy scenarios and the identification of socioeconomic and technological response strategies to these challenges. The modelling framework and the results provide core inputs for major international assessments and scenarios studies, such as the Intergovernmental Panel on Climate Change (IPCC), the World Energy Council (WEC), the German Advisory Council on Global Change (WBGU), the European Commission, and most recently the Global Energy Assessment (GEA).

**Business as usual governance of UNECE energy systems will not deliver the change required.** Given the longevity of existing energy infrastructure and the shortage of time to reach carbon neutrality, the role of 'futureproofing' is becoming increasingly important and urgent. Limitations of critical raw material resources required for an energy transition add uncertainty and complexity to the judgments to be made.

**The carbon neutrality scenario modelled for this publication sets a potential path to attain carbon neutrality by 2050** using a 'middle of the road' socio-economic outlook to determine energy demand. The model starts with current UNECE energy systems and considers various energy technologies' costs and lead times to estimate the technologies and capacities required for the least system cost energy supply to support the underlying economic growth assumptions. By imposing constraints, such as GHG emissions consistent with net-zero emissions by 2050, the energy supply mix will change to attain a carbon-neutral scenario. The model also details investments in energy infrastructure and trade from resource extraction to distribution.

**The model accounts for economies of scale.** Costs of energy and lead time for technologies are based on assessments by experts in the technology. The 'cost' calculated includes an allowance for a return on investment to represent an investment case and consists of an estimate of 'cost learning' through developed efficiencies, optimization, and economies of scale. The model considers energy demand, technology, and infrastructure challenge to attain net-zero emissions using low- and zero-carbon technologies alongside existing energy technologies.

## Scenarios definitions

**Reference Scenario**: This scenario is developed on a set of baseline assumptions based on historical trends and current policies. It describes an evaluation of the world as it stands right now. A reference scenario enables analysis of whether the world is likely to achieve specific goals along its current trajectory. Future emissions are determined by the relative economics of a portfolio of current and future supply alternatives and the rates of technology learning and innovation assumptions and trends underlying the reference scenario. Across the publication, the results of carbon neutrality scenarios are compared to a reference scenario.

**Carbon Neutrality Scenario**: The carbon neutrality scenario imposes a mandatory carbon neutrality constraint by 2050 and aims to limit global temperature rises to less than 1.5C by 2100. The scenario assesses the feasibility of carbon neutrality by 2050 under the technology, innovation, and infrastructure assumptions of the reference scenario. Fossil fuel-based supply options become economically less attractive. Renewable and nuclear power heavily replace fossil fuels. Given the portfolio of future supply options, innovation, and technology learning rates of the reference scenario, the carbon neutrality scenario pushes the penetration of these technologies to the limit. Demand-side management effects moderate the pressure on supply.

**Carbon Neutrality Innovation Scenario**: A future characterized by carbon neutrality is distinctly different from the reference scenario and equitable technology assumptions. The carbon neutrality innovation scenario focuses on the potential benefits of innovation and deployment policies that accelerate the market uptake of innovative technologies. These include:

- Carbon capture, use and storage (CCUS) with decarbonized fossil fuels using captured $CO_2$ processed in a circular carbon economy or stored, and the use of direct air capture $CO_2$ from the atmosphere.
- Nuclear power with large-scale reactor designs and new small modular reactors (SMRs), and additional energy services beyond electricity, such as shifts to synfuels, technologies, and industrial processes.
- Hydrogen with the roles of synthetic fuels and hydrogen as direct and indirect end-use fuels.

# CARBON NEUTRALITY AT A GLANCE

In 2022, the UNECE region is nowhere near achieving carbon neutrality. The UNECE region produces 39% of global $CO_2$ emissions, has had high emissions historically, and includes countries with the highest level of economic development in the world. Despite positive commitments by countries, the region is still heavily reliant on fossil fuels. Fossil fuels still account for over 80% of UNECE's energy supply. Although sustainable energy capacity is growing quickly, the growth rate is insufficient.

In a reference scenario, Western Europe and North America will make up over 75% of UNECE's total $CO_2$ emissions in 2050. The electricity and transport sectors contribute over 60% of UNECE emissions due to continued reliance on fossil fuels.

Progress on attaining carbon neutrality and economic development is varied among the sub-regions of UNECE. Therefore, highly developed sub-regions should not only strive toward individual targets, but it is also imperative to support nations for which attaining carbon neutrality is more challenging. Wealthier countries should also strive to be carbon negative to compensate for historical emissions.

FIGURE 5

**Size of Problem – $CO_2$ and $CH_4$ emissions in the UNECE region** [Mt $CO_2$eq]

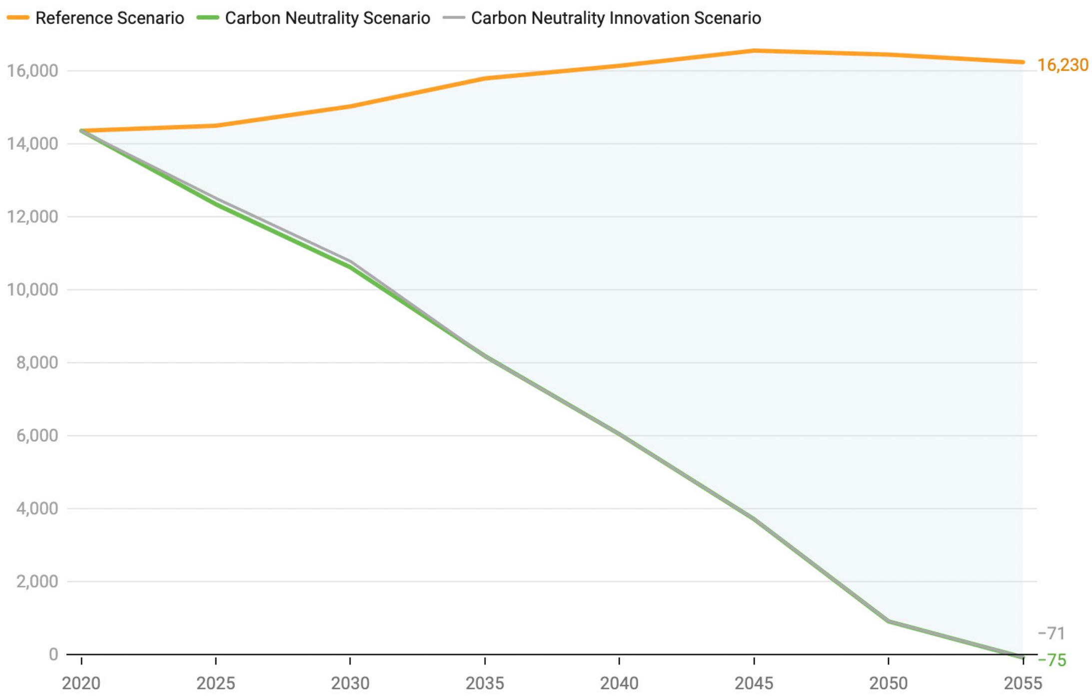
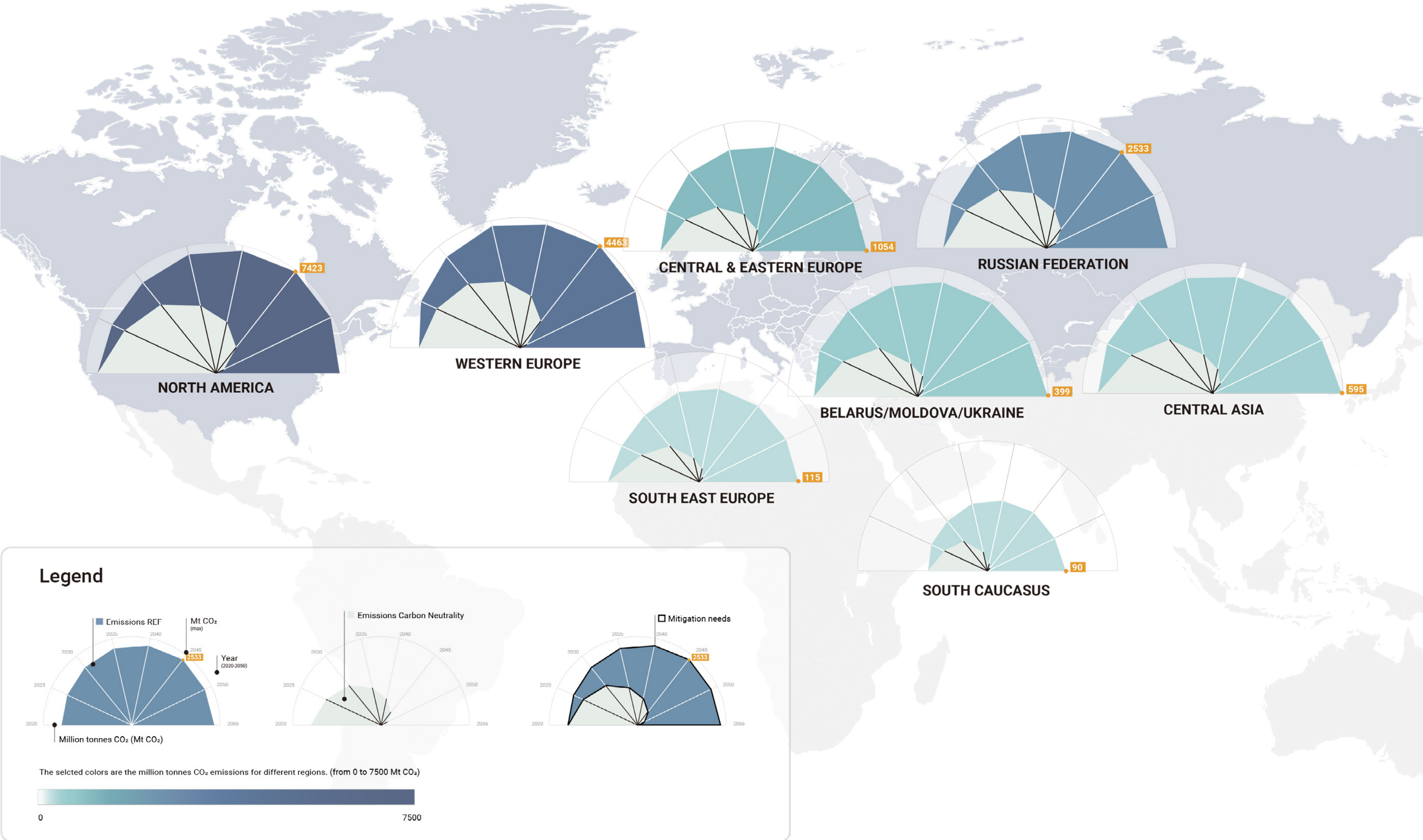


FIGURE 6

**Carbon Neutrality Readiness Level across the UNECE Region – reference and carbon neutrality scenarios comparison of the $CO_2$ and $CH_4$ emissions [Mt $CO_2$eq]**



## $CO_2$ emissions by sectors

**Carbon neutrality requires reducing emissions across all nations and all sectors.** Industry, Buildings, and Transport sectoral emissions must be significantly scaled down.

**Some sectors contribute more than others.** Large sectors such as power generation, transport, and industrial processes are the most significant contributors to $CO_2$ emissions. This is because of their heavy reliance on fossil fuels. In the carbon neutrality scenario, transformed fossil fuels, electricity infrastructure, and land use contribute to offsetting $CO_2$ emissions in cooperation with heavy reductions in emissions from other sectors.

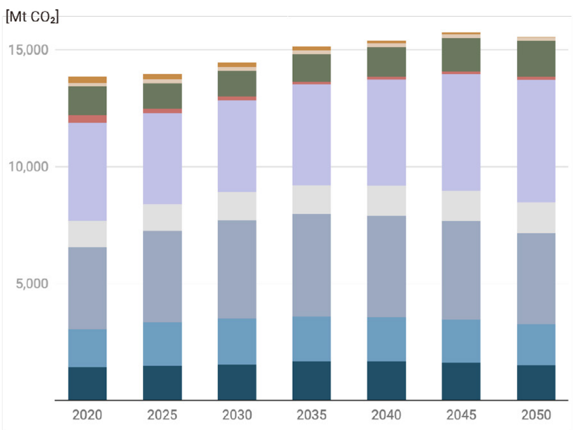
**FIGURE 7**

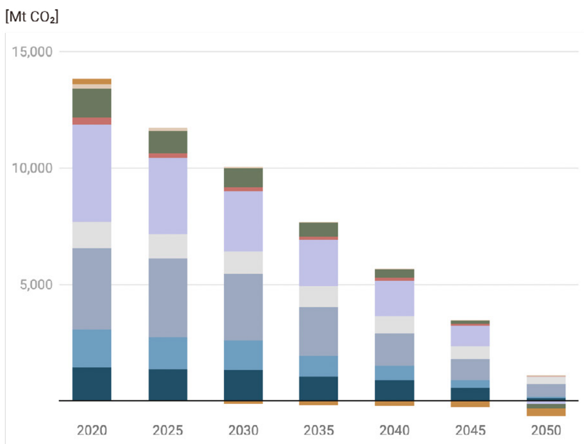
**$CO_2$ Emissions by Sector Reference Scenario** [Million tonnes $CO_2$ [Mt $CO_2$]]

**FIGURE 8**

**$CO_2$ Emissions by Sector Sector Carbon Neutrality Scenario** [Million tonnes $CO_2$ [Mt $CO_2$]]

Industry | Transportation | Buildings | Other demand | Electricity | Heat supply | Fossil fuel supply | Industry process | Land use




## $CH_4$ emissions by sectors

**Agriculture, Forestry, and Other Land Use (AFOLU) continue to be large methane emitters.** A decrease in coal, oil, and gas production reduces emissions from liquids and solids supply and extraction in the carbon neutrality scenario. Waste emissions are also significantly reduced through more substantial methane control.

FIGURE 9

**$CH_4$ Emissions by Sector Reference Scenario** [Million tonnes $CH_4$ [Mt $CH_4$]]

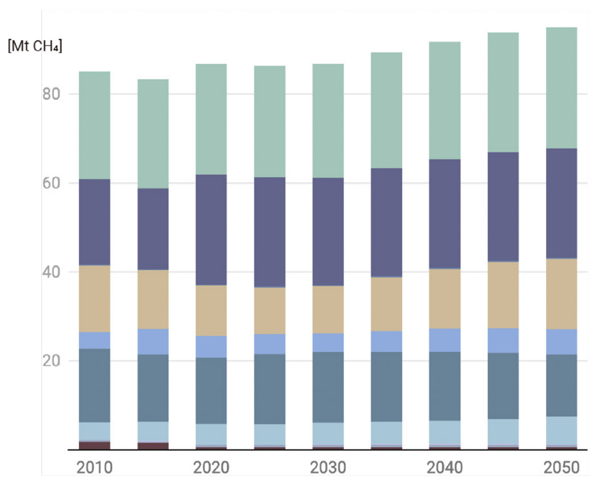
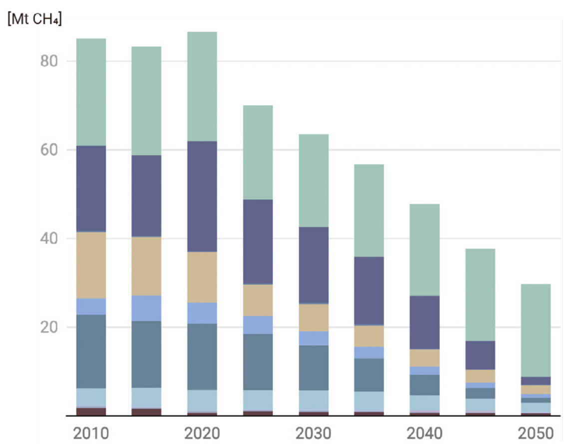



FIGURE 10

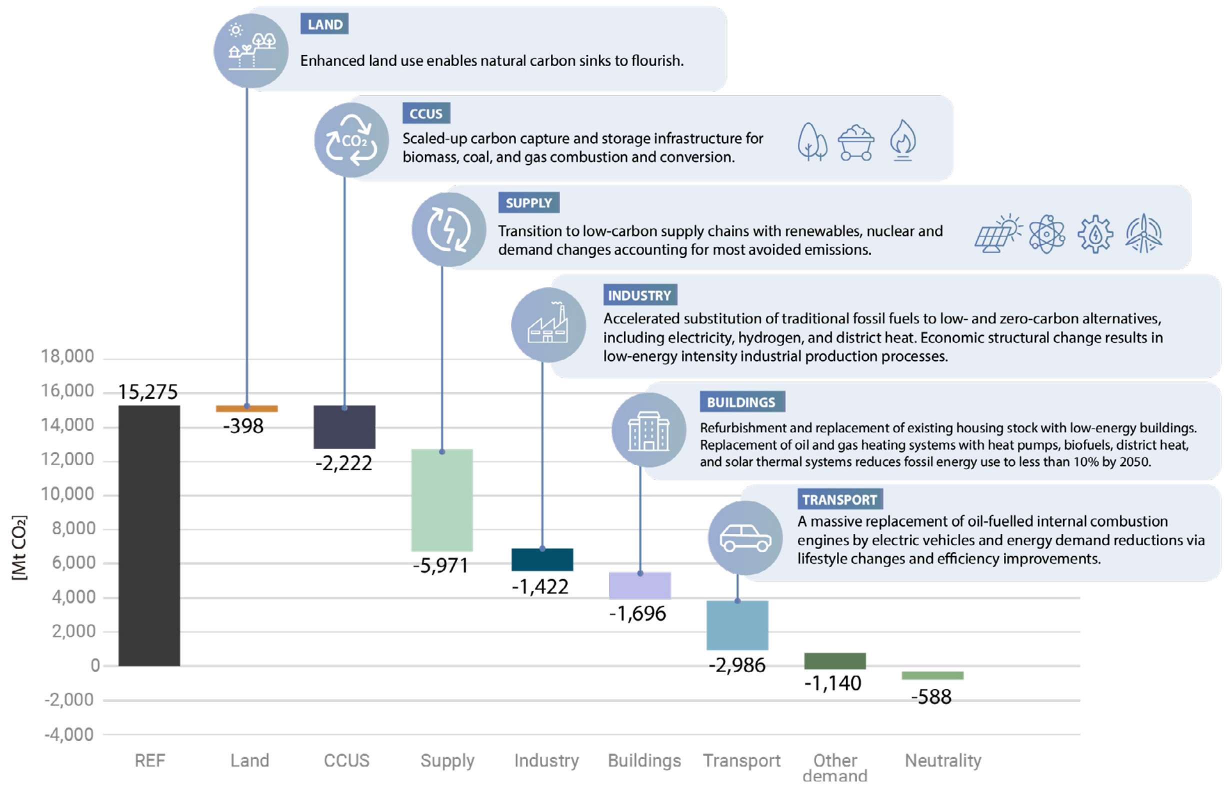
**$CH_4$ Emissions by Sector Sector Carbon Neutrality Scenario** [Million tonnes $CH_4$ [Mt $CH_4$]]




**Methane emissions matter.** Immediately after being emitted, methane ($CH_4$) is 120 times more potent than a climate pollutant carbon dioxide ($CO_2$). Like $CO_2$, methane is currently at record highs in the atmosphere. It is the second most abundant anthropogenic GHG after $CO_2$. Methane's high global warming potential means that its leakages to the atmosphere must be minimized. At a leakage ratio of around 3-4%, the advantage of replacing coal with gas is likely eliminated. Enhanced monitoring and reporting would enable more robust mechanisms to tackle the problem. The oil and gas sector has significant roles in methane management and wider decarbonization of the energy system. Scaling down fossil fuel production will support $CO_2$ and $CH_4$ emissions eductions.

FIGURE 11

**$CO_2$ mitigation** [MtCO2/yr.] **in UNECE, Carbon Neutrality vs Reference Scenarios**[4]




**$CO_2$ emissions will need to be significantly reduced across all sectors in all regions by utilizing all low- and zero-carbon technologies.** No sector of the economy can be ignored, and no technology option can be eliminated. Measures will need to be implemented to address the massive scale of the challenge ahead. Although decarbonizing the energy supply is critical to attaining carbon neutrality, it is only one of many sectors that need to act now. More efficient land use, natural carbon sinks, and carbon capture technologies require sufficient support and investment. Industrial processes and end-uses, including transport and buildings, reduce $CO_2$ emissions.

**A carbon-neutral future is achievable with the right policies, incentives, and technology interplay.** A variety of technologies will be required to scale up at an unprecedented rate. The necessary technologies already exist, and many are economically viable with the addition of appropriate regulatory frameworks. Nonetheless, carbon neutrality will be challenging but imaginable.

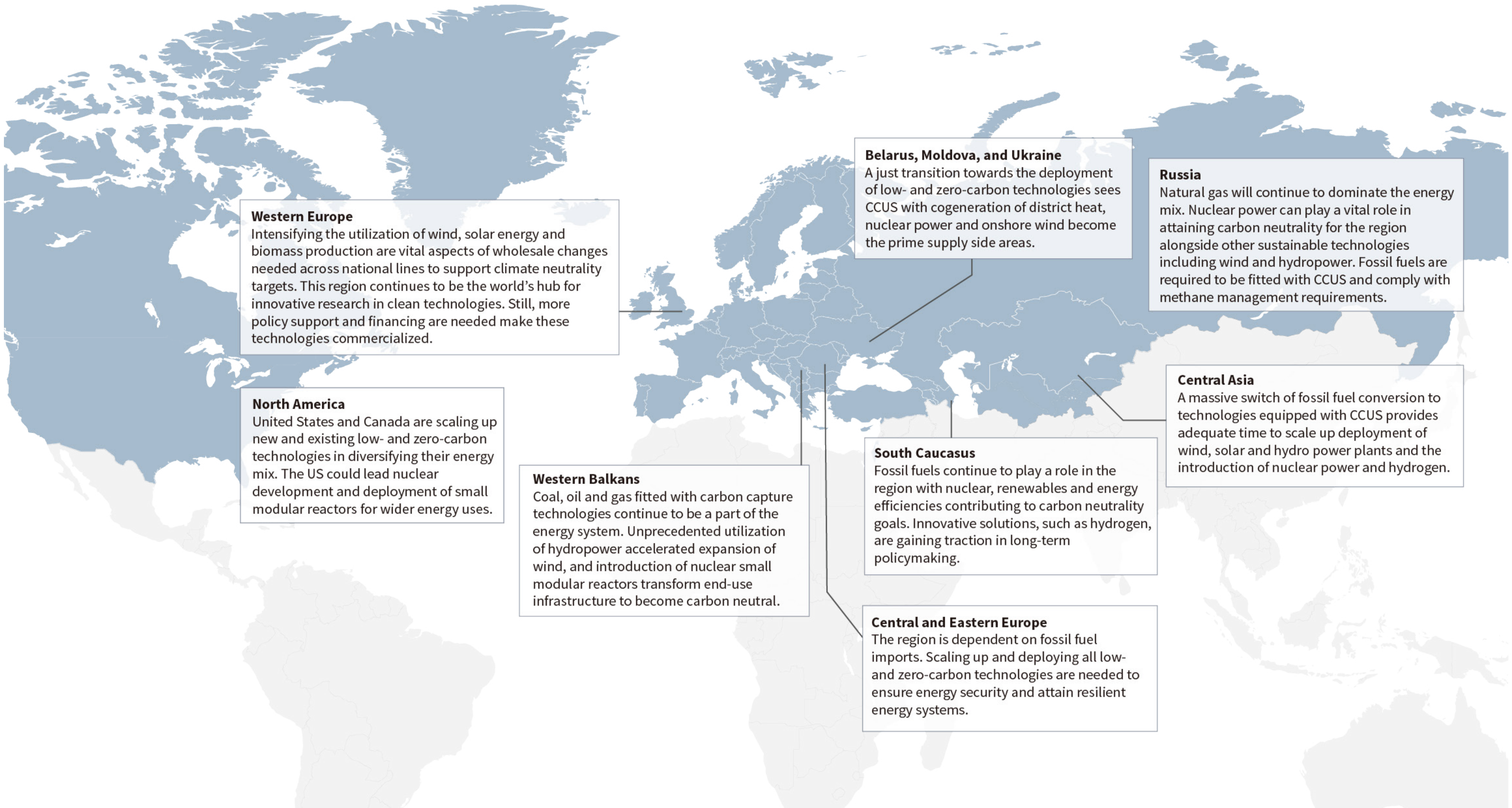
4 Efficiency is defined in terms of economics, price & demand elasticities, lifestyle changes, intensity (MJ/GDP) and engineering efficiency. It does not relate to thermodynamics.
Energy efficiency refers to price-induced reductions in energy demand as a result of the additional cost of the system compared to a reference scenario. This includes both technological and behavioral measures at a high level of aggregation, which are modeled via an iterative link between the energy system and a top-down, macro-economic model for each region.

FIGURE 12

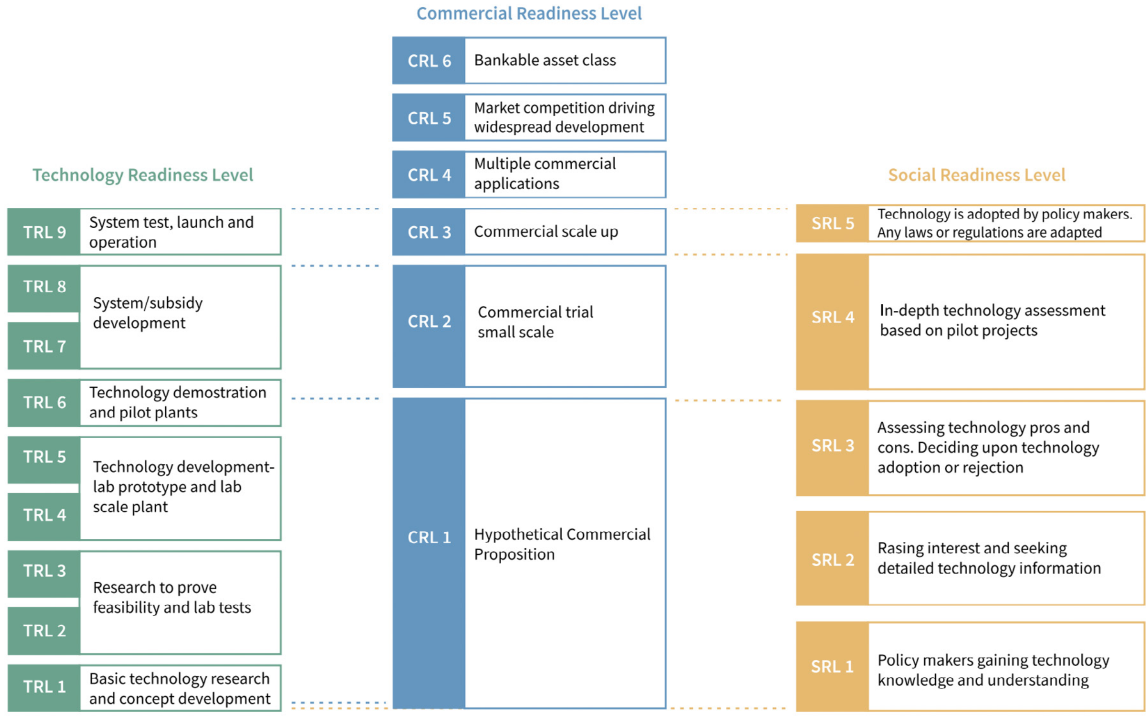
**Subregional Action Required to Reach Carbon Neutrality by 2050**

In general, changing supply technologies to low- and zero-carbon technologies is not enough to attain carbon neutrality. Transforming the energy system to prioritize must include end-use infrastructure such as electric vehicles, charging infrastructure, heat pumps, fuel cells, storage systems.

All regions reduce demand via massive investments in lower energy intensity infrastructures, efficiency improvements and significantly reduced unabated fossil fuel conversion. Sub-regions pivot to a combination of the introduction of CCUS and hydrogen infrastructure, scaling-up renewable energy and nuclear power, and implementing infrastructure for a gigantic penetration of electricity.



## Technology, commercial and social readiness levels




## Action required by technology

| Technology | Required by 2050 in UNECE Region | Compound average growth rate 2020-2050 (%) | Equivalent | Technology Readiness Level | Commercial Readiness Level | Social Readiness Level |
|---|---|---|---|---|---|---|
| Wind | 500,000 wind turbines with a capacity of 2,240 GW generating 6,750 TWh | Capacity: 6.4%<br>Generation: 7.6% | Eleven million tonnes of steel, or 6% of the 2020 global steel production. | ●●●●●●●●● | ●●●●●● | ●●●●● |
| Solar | 7 million utility-scale panels with a total capacity of 2,650 GW generating 4,430 TWh | Capacity: 8.6%<br>Generation: 9.5% | 2.8 million football pitches of solar panels equal to the surface area of Belgium(0.07%) of the whole UNECE region. | ●●●●●●●●● | ●●●●●● | ●●●●● |
| Hydropower | Expanding hydropower capacity to 720 GW generating 2,500 TWh | Capacity: 1.4%<br>Generation: 1.5% | Adding net 250 GW, the equivalent of 13 Three Gorges Dams. | ●●●●●●●●● | ●●●●●● | ●●●●○ |
| Geothermal | 25 times larger electricity generating capacity than 2020 (120 GW in 2050) | Capacity: 11.3%<br>Generation: 11.3% | Global geo-capacity electricity in 2020: 14.1 GW. UNECE expansion is equivalent to 8-9 times the current global capacity | ●●●●●●●●● | ●●●●○○ | ●●●●● |

| Technology | Required by 2050 in UNECE Region | Compound average growth rate 2020-2050 (%) | Equivalent | Technology Readiness Level | Commercial Readiness Level | Social Readiness Level |
|---|---|---|---|---|---|---|
| Bioenergy | 25 GW decrease in biomass sourced electricity w/o CCUS from today's levels and 27 GW increase of biomass with CCUS (today <1GW) | Non CCUS equipped Capacity: (-2.3%)<br>Generation: (-1.8%) | Continuous shift to biomass with CCUS. Total biomass generation will double from today's levels by 2050 (>72% with CCUS) | ●●● ●●● ●○○ | ●●● ●○○ | ●●● ○○ |
| Nuclear power | A total capacity of 604 GW generating 4,400 TWh | Capacity: 2.6%<br>Generation: 2.9% | Adding net 390 GW | ●●● ●●● ●●● | ●●● ●●● | ●●● ○○ |
| Fossil Fuels | 54% decrease (-740 GW) in non-CCUS equipped fossil-fueled capacity but 420 GW new CCUS equipped capacity | Non CCUS equipped Capacity: (-2.5%) Generation: (-8%) | Generation with CCUS: 2,810 TWh | ●●● ●●● ●●● | ●●● ●●● | ●○○ ○○ |
| CCUS | Two years of current global $CO_2$ emissions (46 Gt of $CO_2$ captured) | | 46 Gt $CO_2$ to be stored corresponds approx. To 25% of the volume of global natural reserves in 2020 | ●●● ●●● ●○○ | ●●● ○○○ | ●●● ○○ |
| Hydrogen | By 2050 some 7.68 EJ or 64 Mt $H_2$ are used – essentially from 0 in 2020 | Use 4.1% | 64 Mt $H_2$ can fuel<br>1) 730,480 Saturn V (Apollo 11) missions to the moon<br>2) fill 3.5 million Hindenburg dirigibles<br>3) Operate for one year 7.5 million fuel cell equipped Class 8 trucks (heavy trucks) in the US, driving on average 62,750 miles per vehicle and year: Current Class 8 trucks registered in the US 3.97 Million | ●●● ●●● ○○○ | ●●● ○○○ | ●●○ ○○ |
| Energy Efficiency | Double the decline of final energy intensities compared to historical trends. | Improvement (decline of final energy intensities): 2.5% | Decline in total FE of 32 EJ (-20%) while GDP grows by 70% | ●●● ●●● ●●● | ●●● ●●● | ●●● ●● |

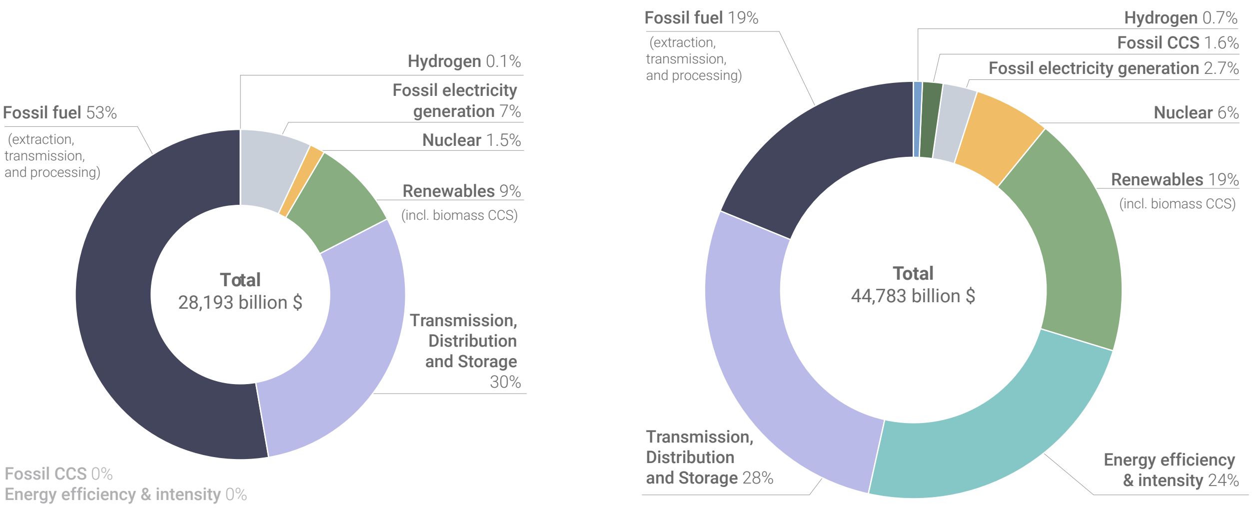
This table includes a Technology, Commercial, and Social Readiness Level, which features in UNECE's Technology Briefs. Readiness levels are inspired by the United Nations Framework Classification for Resources (UNFC) - a universally acceptable and internationally applicable scheme for the sustainable management of all energy and mineral resources. Policymakers can use these frameworks to assess where to focus investments and which technologies. [See Annex I.]

# Investments are needed across all low- and zero-carbon technologies

**Carbon Neutrality requires a significant shift in the allocation of investment in the future energy systems.** Modelling shows fossil fuel extraction investment diverted to other sectors of the energy system. Investment in renewable energy is quadrupled, and investments in energy efficiency are growing to become a quarter of total energy investments. Significant investment increases are also seen in nuclear power, CCUS, and hydrogen.

**FIGURE 13**

**Total Investment Needs for UNECE Energy Systems Reference and Carbon Neutrality Scenarios**



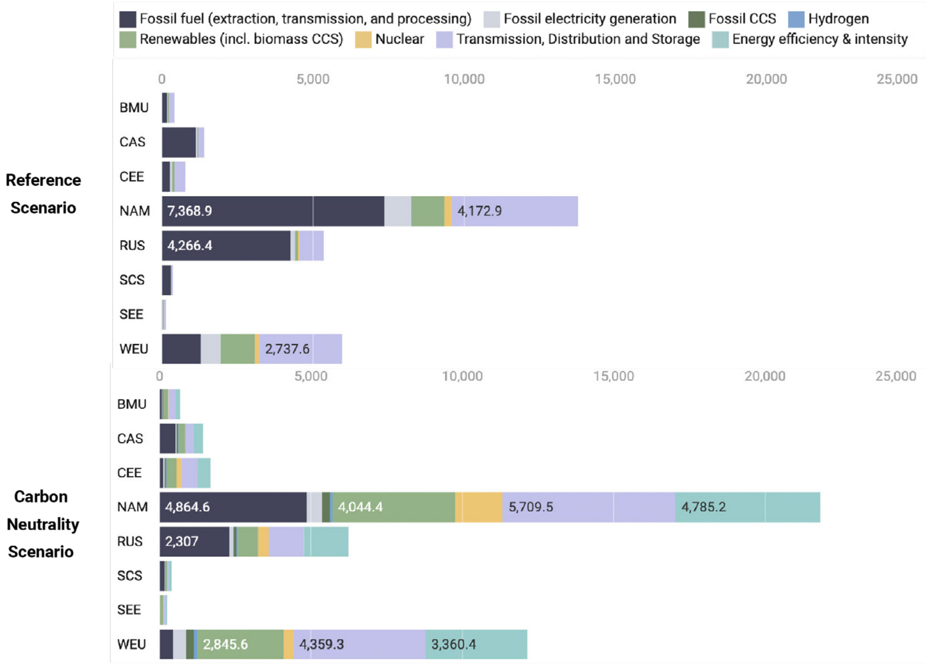

**Reference Scenario**
Total Investment Needs 2020

**Carbon Neutrality Scenario**
Total Investment Needs 2050

# Investing in clean energy infrastructure across UNECE subregions

**FIGURE 14**

**Total Investment Needs for UNECE Energy Systems Reference and Carbon Neutrality Scenarios by Subregions**




**All regions must re-direct resources now before it is too late.** Significant investment in energy efficiency and transmission, distribution, and storage benefits all stakeholders. Consumers can benefit from lower energy costs with more energy-efficient homes. Energy providers and industries can also reduce energy production costs with modernized energy transmission and storage.

**Policymakers and the financial world must develop investment frameworks for all low-carbon energy projects.** Governments should support development projects with an appropriate risk-sharing structure and facilitate access to low-cost financing, to accelerate the deployment of innovative technologies. Consistent policies and market frameworks are needed to provide favorable investment signals and attract private finance for high capital cost projects. Policymakers need to be empowered and encouraged to make strong investment decisions.

## How much will the transition to net-zero cost?

The cost to transition to carbon neutral energy systems are much lower than perceived. The cost of inaction is far greater as vulnerable energy systems are susceptible to the environmental, economic and social consequences of climate change.

**Energy investment as % of GDP (Gross Domestic Product)** slightly declines from 1.24% in 2020 to 1.05% by 2050 in a reference scenario. To attain carbon neutrality, energy investment share must increase to 2.05% from 2025. This is a moderate increase but will increase if procrastination persists. A lack of action is likely to make climate compatibility more expensive and burdensome to future generations. Therefore, raising awareness about investment merits is essential to counter socio-political acceptance concerns.

**Energy expenditure for final energy as a share of GDP** can show the marginal values along each step of the energy delivery chain because it includes operating, maintenance, and fuel costs. The reference scenario sees a moderate increase from 6.2% in 2020 to 8.0% by 2050. In the carbon neutrality scenario, energy and energy services investments increase to 15.2% of GDP.

# ENERGY SYSTEMS OF THE FUTURE: UNECE REGION

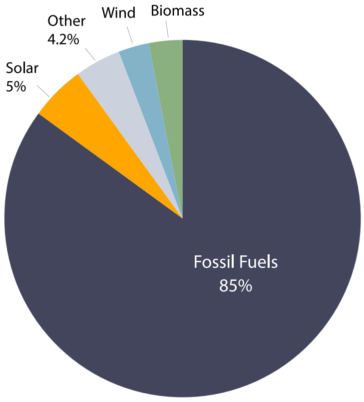
**A rapid transition from fossil fuels to low- and zero-carbon technologies is vital to achieving net-zero emissions.** According to analysis, traditional fossil fuel use will decrease as technologies such as solar and wind, nuclear power, hydrogen, and CCUS make progress. The practical delivery of any rapid pathway to carbon neutrality will be subject to infrastructure capacity and access to natural resources.

**Energy system resilience can be strengthened in several ways** through improvements in energy efficiency, diversification of energy supply, and interconnected infrastructure of all low- and zero-carbon technologies. In addition, technology development and investment strategies must form part of the broader climate policies.

**Low- and zero-carbon solutions must be prioritized and built at scale to ensure carbon neutrality targets are met.** If we continue with business as usual, the world is on a path to global average temperatures that are 4-6°C above pre-industrial levels. These levels are considered catastrophic and existential threats to humanity that must be addressed urgently.

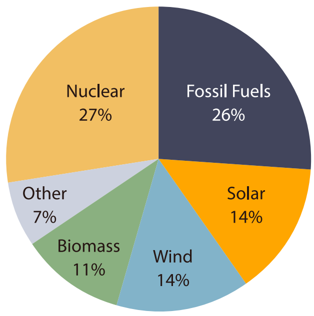
**FIGURE 15**

**Total Primary Energy Supply for 2050** [EJ] **Reference Scenario vs Carbon Neutrality Scenario**




**Reference Scenario**

Primary Energy Supply 2050

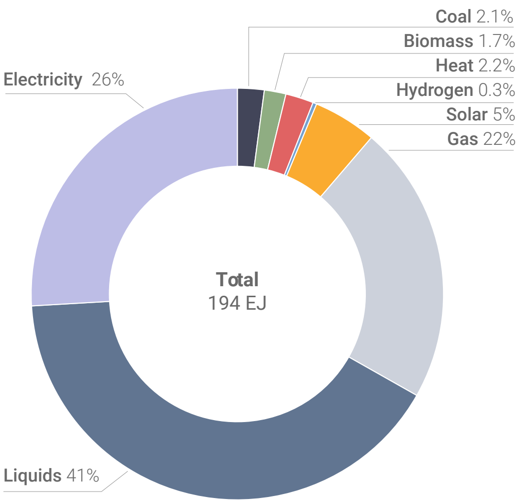



**Carbon Neutrality Scenario**

Primary Energy Supply 2050

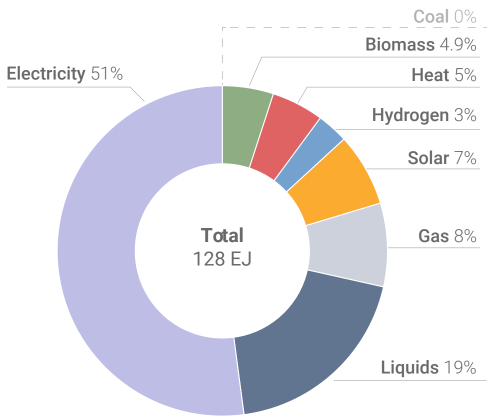
**FIGURE 16**

**Final Energy Supply for 2050** [EJ] **Reference Scenario vs Carbon Neutrality Scenario**




**Reference Scenario**

Final Energy Supply 2050



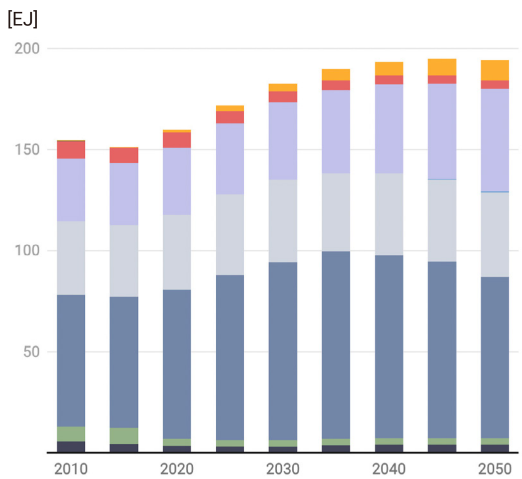

**Carbon Neutrality Scenario**

Final Energy Supply 2050

# Final energy supply

**FIGURE 17**

**Final Energy Supply** [EJ] **Reference Scenario**

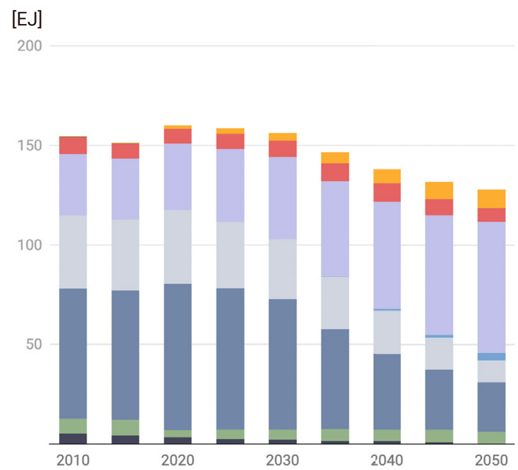



**Reference Scenario**

Final Energy Supply 2050

**FIGURE 18**

**Final Energy Supply** [EJ] **Carbon Neutrality Scenario**

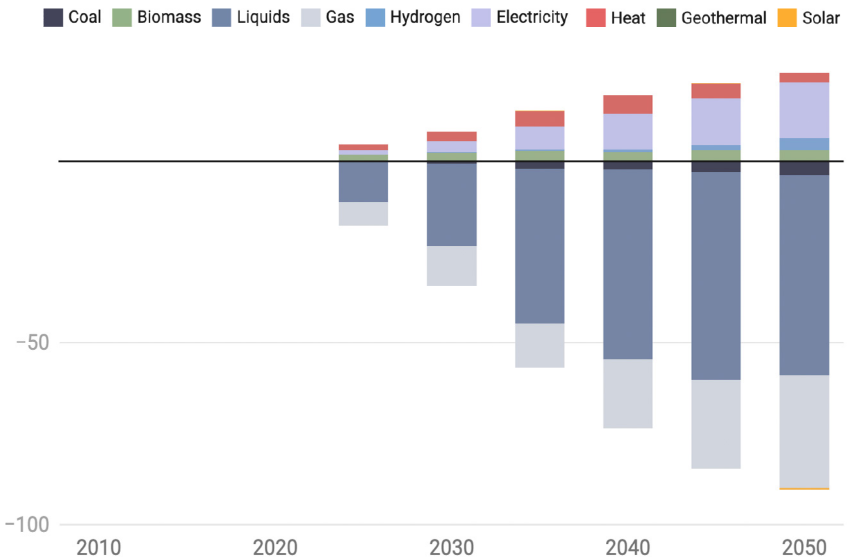



**Carbon Neutrality Scenario**

Final Energy Supply 2050

**FIGURE 19**

**Final Energy Supply [EJ]: Comparison between Carbon Neutrality and Reference Scenarios**



**The final energy supply** indicates energy carriers used to deliver to end-users. In the context of this project and modelling exercise, this includes:

- **Electricity** is used for lighting, appliances, and other electric equipment. It is also used in electric heating, heat pumps, and cooling in buildings. It facilitates the electrification of industrial processes such as electric furnaces and electric transportation.
- **Solar thermal** is used for heating purposes in buildings and industry.
- **Geothermal** is used in buildings and industry for heating.
- **Heat** is district heating, including block heating and heat from industrial cogeneration.
- **Hydrogen** is fuel for transportation such as fuel cell vehicles, providing process heat in industrial processes such as steel and ammonia production. Hydrogen powers fuel cells generating heat and electricity in buildings and industry.
- **Gas** is used for cooking and heating in buildings, heat in industrial processes, and low-carbon fuel in transport.
- **Liquids** include both fossil and synthesized renewable-based fuels. It provides light and heavy fuel oil and bioliquids such as ethanol and methanol. Liquids are used for heating/cooling and cooking in buildings, process heat, and feedstock in industry.
- **Biomass** is used for heating in residential and commercial sectors and industries.
- **Coal** is used for burning in boilers and cookers in buildings and for process heat and feedstock in industries such as steel and cement production.

The transition from the current final energy mix to a carbon-neutral one will require structural changes. A carbon-neutral final energy supply requires improvements in energy intensity, fuel-switching from traditional to low- and zero-carbon fuels, and deep electrification.

**Energy efficiency is a low-hanging fruit** solution that can significantly reduce energy demand and improve the carbon intensity of the final energy system. Improved energy efficiency will be needed across industry, transport, and building sectors and would require effective action-oriented campaigns designed to unlock this potential.

**System efficiency goes beyond energy demand optimization.** Enhanced material efficiency and recycling have gained importance for raw materials in the circular economy. To increase resilience against external shocks, improvements in recyclability and repairability towards full circularity can reduce emissions, access, and cost of raw materials.

**System-wide digitalization** has the potential to bridge gaps at the system level while catalyzing new opportunities. Digital technologies can unlock massive potential with demand-side flexibility, which could be a key instrument for balancing the grid and cost-effectively achieving net-zero.

**Widespread innovation of low- and zero-carbon technologies reduces the carbon intensity of the energy systems.** Alongside the efforts to improve energy efficiency and digitalization, fuel-switching from traditional energy sources to lower carbon fuels such as natural gas, biofuels, and biomass will be needed. It is expected that the next generation of low- and zero-carbon fuels, such as hydrogen and synthetic fuels, will be scaled and fully commercialized.

**Sustainable hydrogen** from renewable energy and nuclear power through electrolysis, natural gas, coal, and biomass with CCUS has the potential to decarbonize hard-to-abate sectors, such as long-haul transport or energy-intensive industries. Hydrogen is expected to play an increasingly significant role from 2040 in a carbon-neutral energy system.

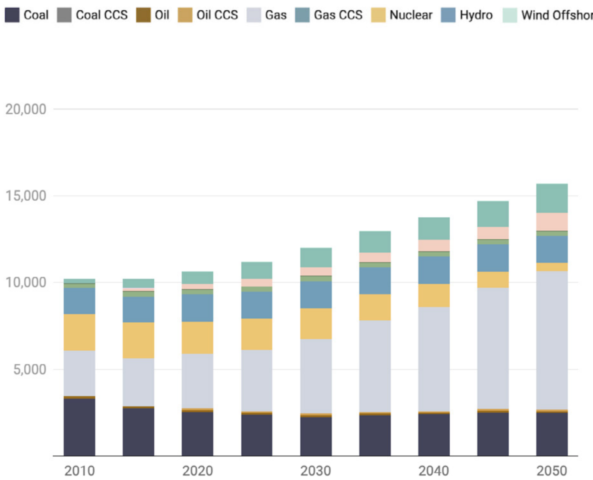
**The biggest $CO_2$ emission reductions require scaling up the electrification of the final energy system.** Energy supply is reduced by 35% in a carbon neutrality scenario because fossil fuels are displaced by renewable energy, nuclear power, and improved energy efficiency. Energy demand also calls for electrification across all sectors, including industry, buildings, and transport. Cohesive interdependence of cross-sectoral and regional electricity systems will enable the phase-out of carbon-intensive fuels and significantly reduce carbon emissions.

**The impact of doubling electricity demand will have knock-on effects.** Electrification still implies a doubling of electrical demand. This will require the installation of more transmission cables to enhance capacity and efficiency. The electricity system's reliability will become more critical as it risks becoming a single point of failure that will impact every aspect of life. The increase in electricity capacity should be in advance of the increase in demand to avoid electricity blackouts and excessive energy prices when demand outstrips supply. The UNECE region will increasingly have to balance short-term supply with demand. The lack of technology to store electrical energy greatly reduces the ability to cope with energy supply changes over a longer period.

## Electricity generation mix

**FIGURE 20**

**Electricity Generation Mix** [TWh] **Reference Scenario**

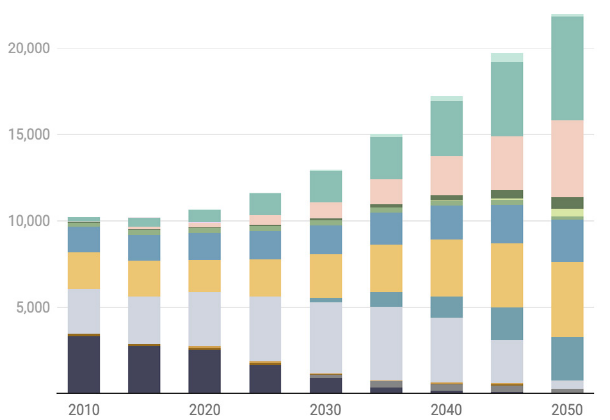



**Reference Scenario**

Electricity Generation Mix 2020

**FIGURE 21**

**Electricity Generation Mix** [TWh] **Carbon Neutrality Scenario**

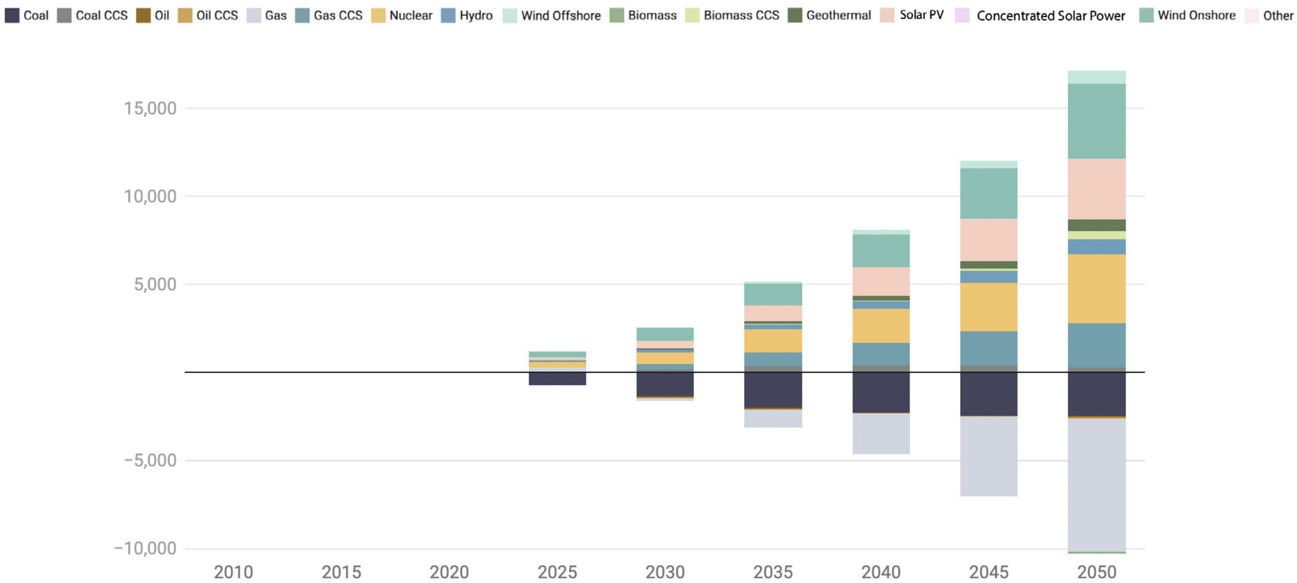



**Carbon Neutrality Scenario**

Electricity Generation Mix 2050

**FIGURE 22**

**Electricity Generation Mix** [TWh]**: Comparison between Carbon Neutrality and Reference Scenarios**



**Today's electricity generation mix in the UNECE region** is based on fossil fuels (coal and natural gas), followed by nuclear power and hydropower. Traditional electricity supply systems are characterized by large-scale plants that generate single-directional, fossil fuel-based power for end-users. To attain carbon neutrality, the power generation in the UNECE region will have to experience notable structural changes. The future power generation system will, in part, have to include decentralized and smart systems and require CCUS to mitigate $CO_2$ emissions from coal, gas, and biomass power plants.

**Traditional coal cannot remain a widely distributed source of power generation in the UNECE region.** Coal generation's emissions intensity is incompatible with environmental goals. As such, efforts to quickly invest in and deploy carbon capture, use and storage (CCUS) and high-efficiency, low-emissions (HELE) retrofit technologies around existing coal generation should be considered, especially for parts of the UNECE region without viable alternatives.

**Renewable energy, nuclear power and gas with CCUS** will be the main elements of a future power system. For each GW of fossil capacity phased out, 2.6 GW of low carbon capacity is expected to be built - of which 75% is intermittent renewable energy. Deployment of distributed renewable energy generation projects would reduce losses in the grid and minimize electricity flows. New ways to compensate for highly variable energy sources will be needed. New forms of energy storage (electric, mechanical, thermal, chemical) should be developed to decrease the need for fossil energy backups. The concept of ´baseload' energy will be replaced by 'uninterruptable' energy – this implies that the supplies cannot be allowed to be turned off for critical uses.

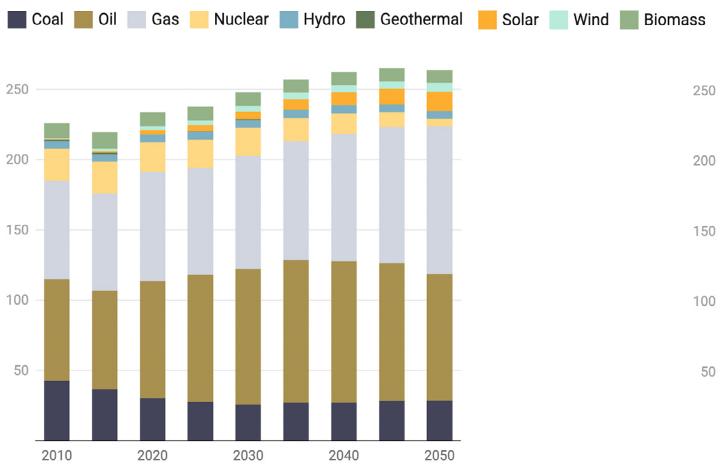
## Do carbon neutrality scenarios reflect 'efforts towards phasedown of coal'?

**Coal use is drastically reduced in all the modelled carbon neutrality scenarios.** The modelling looks at technologies' costs and lead times to optimize how carbon neutrality is achieved. The use of coal with CCUS may well be 'economically' optimal in some countries, given additional modelling conditions, such as energy security, availability of CCUS sites, and political preferences. For example, coal is used together with CCUS to generate hydrogen in model cases where natural gas or renewable energy is not practical in some modelled scenarios. In such cases, the target is to achieve carbon neutrality using different technologies ($CO_2$ and $CH_4$ emissions are either captured or offset to meet the target for emissions).

## Primary energy supply

**FIGURE 23**

**Primary Energy Mix** [EJ] **Reference Scenario**

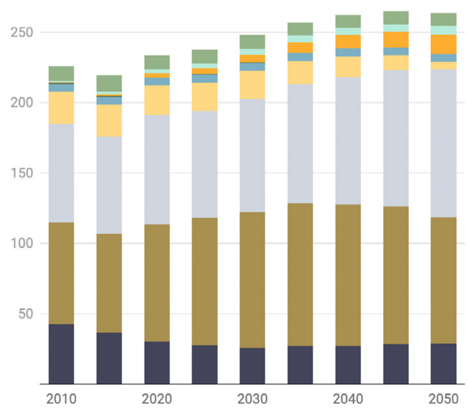



**Reference Scenario**

Primary Energy Mix 2020

**FIGURE 24**

**Primary Energy Mix** [EJ] **Carbon Neutrality Scenario**

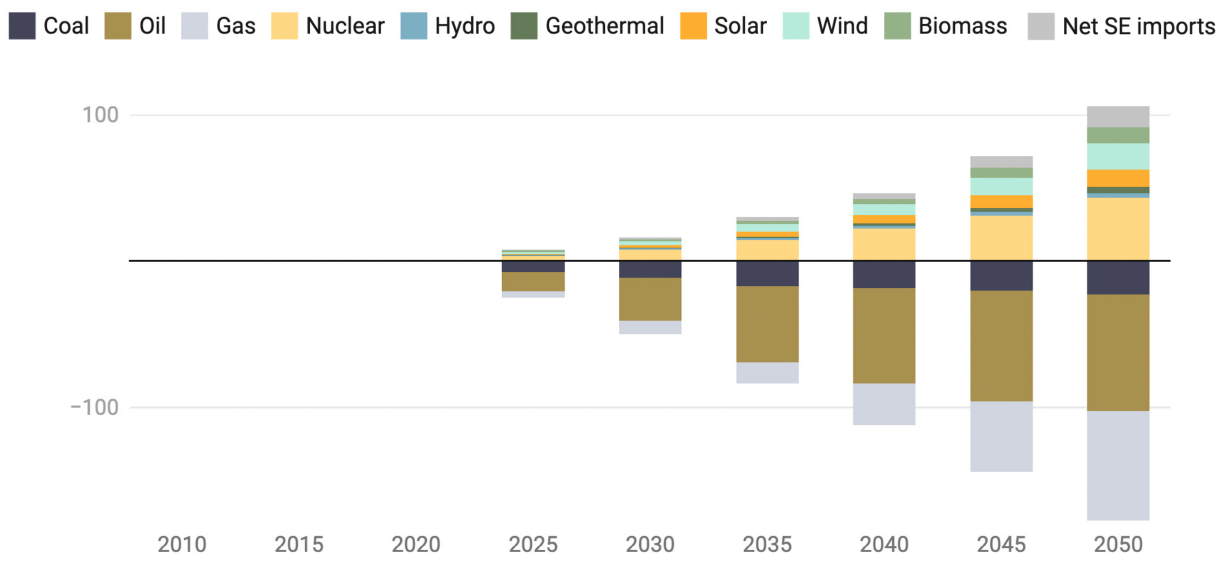



**Carbon Neutrality Scenario**

Primary Energy Mix 2050

**FIGURE 25**

**Primary Energy Mix** [EJ]**: Comparison between Carbon Neutrality and Reference Scenarios**




**carbon neutrality will require unprecedented reductions in energy intensities of 2.5% annually between 2020 and 2050.** Improvements in energy intensities will be due to economic restructuring and the extensive reallocation of resources in the energy system. The phase-out of fossil fuels will result in a fall in primary energy achieved through an integrated and intelligent design that meets demand via clean electrification, smart digital technology, efficient buildings and infrastructure, and a circular economy approach to water, waste, and materials. This is embedded in a whole system approach towards structural change in technology, lifestyle, and economy.

**Primary energy offers efficiency improvements.** Energy efficiency and intensity improvements occur entirely along these chains. Conversion from primary energy into electricity generation, refining, and synfuel production can become more efficient. In addition, the transmission and distribution of energy and end-use sectors, including buildings, transport, and industry, are also principal actors in attaining carbon neutrality.

**Coal, oil, and natural gas in the total energy supply will need to decrease significantly.** To achieve carbon neutrality by 2050, renewable energy supply will grow fastest, followed by nuclear power. All technology solutions leading to carbon neutrality need to be supported. For example, with flexible policy incentives to scale up access to onshore and offshore sites for wind and solar, permits for new nuclear plants, and permits plus funding for geological CCUS. The success of policies to promote renewable energy needs to be considered to kick start the move to alternative energy vehicles, CCUS, small nuclear power modular reactors, and new energy storage systems.

**Energy systems will become reliant on access to critical raw materials.** Vast quantities of raw materials, including critical raw materials, are required for the current and future energy systems. UNECE member States should apply the principles and requirements of the United Nations Resource Management System (UNRMS), which stresses resources as a service, value-addition, circularity, and innovation.

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# INNOVATIVE SOLUTIONS FOR A CARBON-NEUTRAL ENERGY SYSTEM

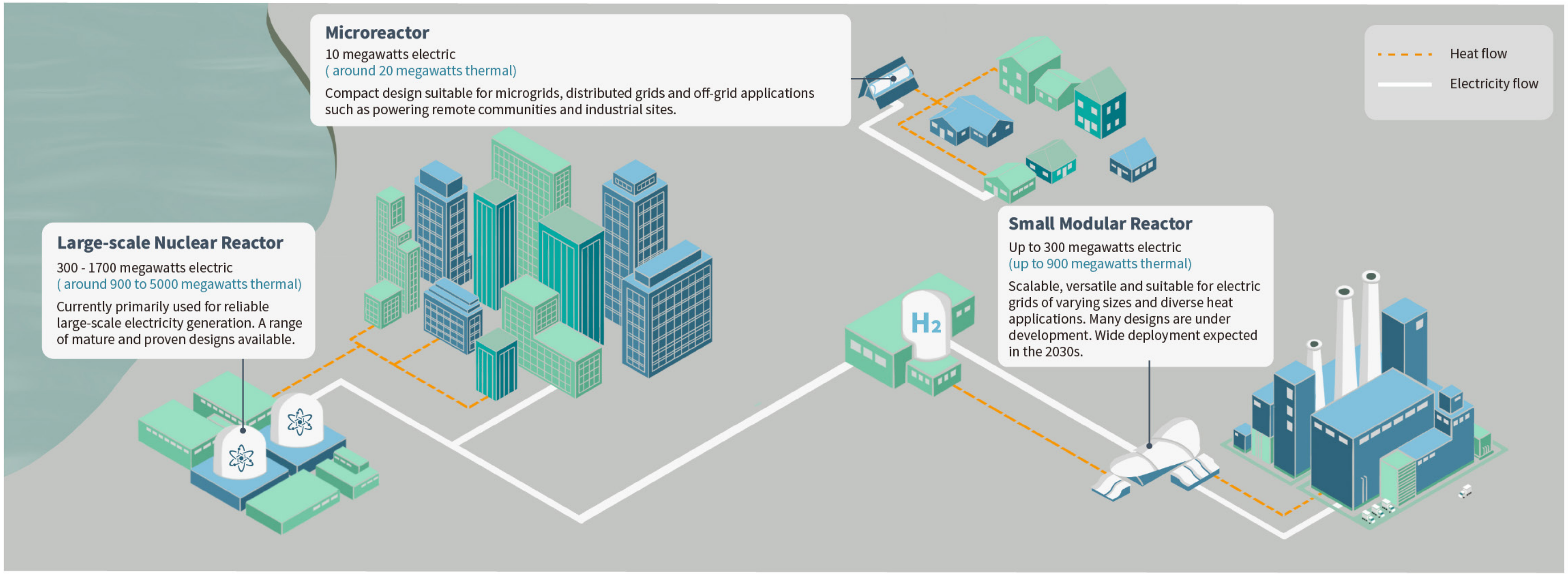
**Innovation will be at the core of a carbon-neutral energy systems.** The world started considering the transformation of energy systems over half a century ago. The non-energy sectors started this transformation much more recently. Typically, technology cycles span over 100 years. Policymakers should expect and be open to a series of innovations within the next decades.

**Deployment of all low- and zero-carbon technologies will advance carbon neutrality.** To make this a reality, the UNECE region must scale-up technology transfer and deployment, expand institutional capacity, and build support for a secure, affordable, and carbon-neutral energy systems.

The next section of this report provides a high-level overview of the properties and the potential of three innovative low- and zero-carbon technologies: a new generation of nuclear power, CCUS, and hydrogen - to deliver on carbon neutrality.

# NUCLEAR POWER

Nuclear power is an important source of low-carbon electricity and heat that contributes to attaining carbon neutrality




## ELECTRICITY GENERATION

Nuclear power plants can produce reliable 24/7 electricity or operate flexibly as required. Dispatchable electricity sources are essential for keeping the costs of the overall system low.

## HYDROGEN


Nuclear power can be used to produce low-carbon hydrogen via several process:

· Low-temperature electrolysis - using nuclear electricity
· Steam electrolysis - using nuclear heat and electricity
· Thermochemical process - using nuclear heat at above 600℃

## PROCESS HEAT FOR INDUSTRY

High-temperature heat from nuclear plants can be transformative in decarbonising hard-to-abate sectors.

## DISTRIC HEATING

Nuclear plants are a proven source of heat for urban district heating that have operated successfully in a number of countries.

**Raising Awareness**
Recognise that nuclear power is a source of low-carbon energy and heat that can help decarbonise energy systems

**Promoting Acceptance**
Develop policies that instil confidence and facilitate the wider application of nuclear power to decarbonise electricity and energy intensive industries

**Incentivising Finance**
Develop financing frameworks that instil confidence and incentivise affordable public and private investment in support of new nuclear power projects

Designed by Shuyue Li

# Advanced nuclear power

**Nuclear power is an essential low-carbon electricity and heat source contributing to carbon neutrality.** Along with current proven commercialized reactor designs, many new nuclear reactor technologies are being developed, which may open new markets, such as better load management, high-temperature heat for industrial processes, combined heat and power production, and electrolysis for hydrogen production. Countries that decide to deploy nuclear power can play an essential role in decarbonizing the UNECE energy systems.

The technology brief on nuclear power represents the potential role of nuclear power in achieving the net-zero emission target and has motivated some nations to look for all the potential low-carbon energy services provided by nuclear power. Some countries may choose to pursue nuclear power with a view that it can play an important role in their energy mix as a viable decarbonization option. Other countries have decided not to use nuclear power for a variety of reasons, some because of their endowment of natural resources and others because of their concerns relating to safety and waste. However, societies are increasingly aware of the risk of failing to reach climate targets. The push for decarbonization of energy systems, alongside increased energy prices and improved safety measures are changing people's attitudes towards nuclear power. This will create new markets for the penetration of the current large-scale reactors and the advanced nuclear power technologies. Policy support is needed to mitigate the financial risk and high capital cost of completing large-scale nuclear power plants and accelerate the development and deployment of small modular reactors (SMRs..

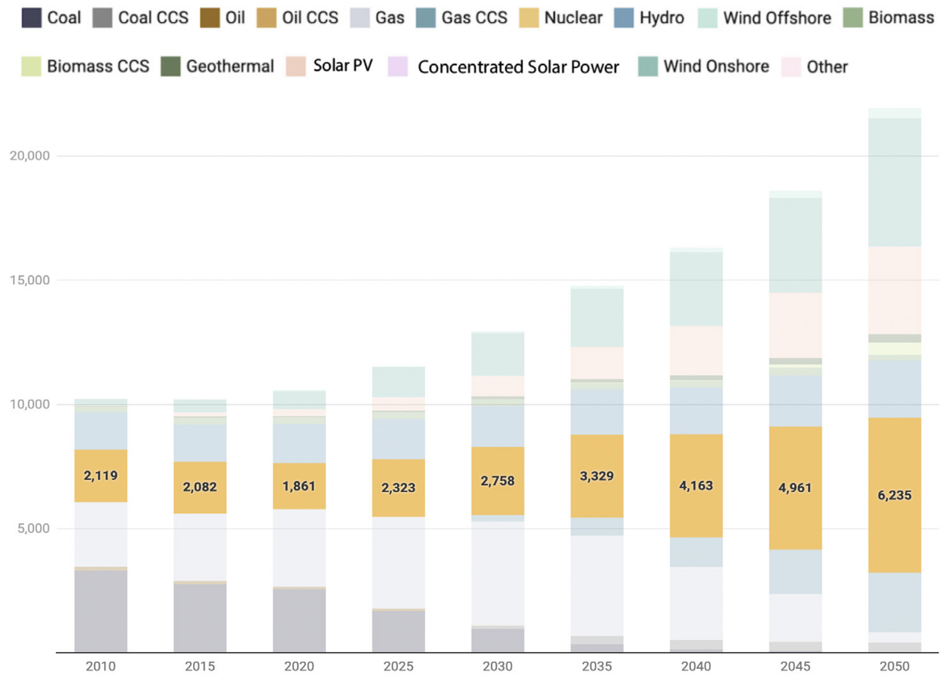
Nuclear SMR technology can provide a range of energy services, including electricity, cogeneration of heat and electricity, and high-temperature heat for industry. The model assumed capital cost assumptions per unit of power rating ($/kW are equal to large reactors but with a much shorter construction time. Large-scale nuclear plants are represented with the possibility of operation in two modes:

- baseload mode with a high-capacity factor of 95% with low flexibility
- flexible mode with 75% capacity factor and flexibility as high as combined cycle gas power plants..

In terms of energy security, extending the operational lifetime of existing reactors that can continue safe operation can significantly ease the use and dependency on fossil fuels and the cost of energy without the financial risks and long-term obligations attached to new energy projects.

FIGURE 26

**Electricity Generation Mix [TWh] Carbon Neutrality Innovation Scenario**



## Nuclear small modular reactors

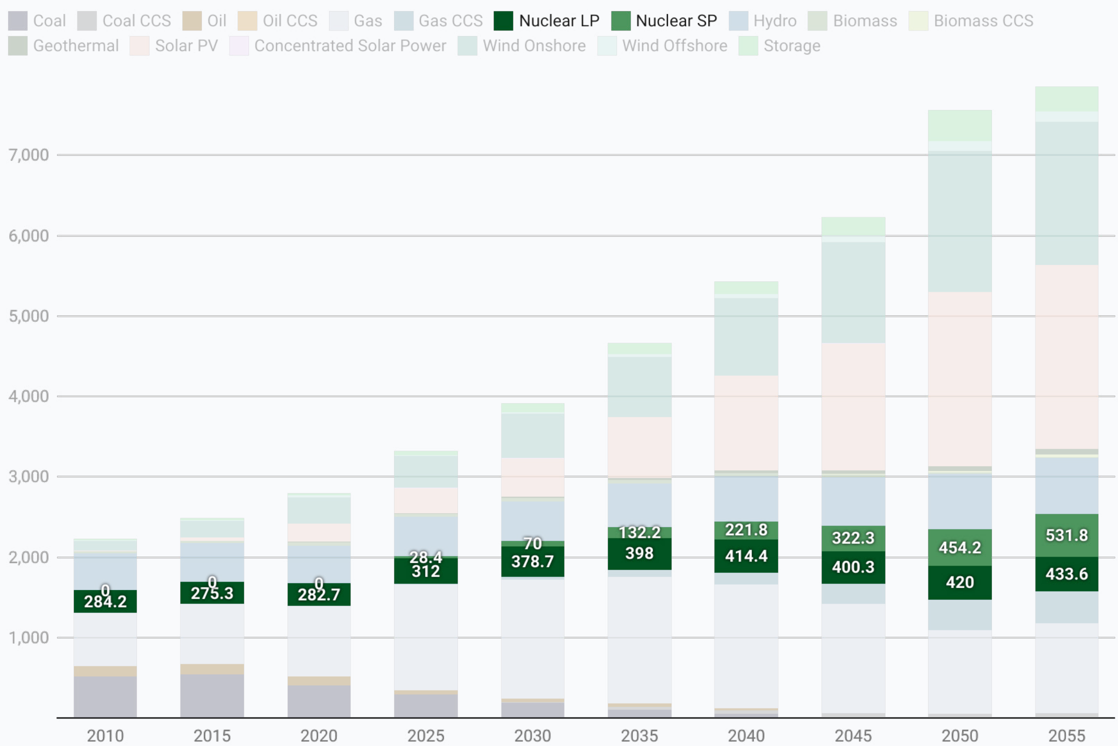
Small Modular Reactors (SMRs) along with the large scale reactors re modelled in a Carbon Neutrality Innovation Scenario. They include the possibility of contributing flexible operations to the power system. In addition, they provide low-temperature district heat (DH) in cogeneration mode and produce high-temperature process heat to be used in industry, replacing fossil fuels. In the future, SMRs combine high-temperature heat with other processes to scale up sustainable hydrogen production. It is foreseen that SMRs have lower construction time due to modularity and small-size reactors.

**Nuclear power is suited to delivering substantial amounts of low-carbon power using little land.** From an environmental life cycle perspective, nuclear power has been shown to be low carbon but also presents a number of co-benefits. It causes low land occupation and transformation over the life cycle due to the high energy density of fuel elements, which minimizes mining area per kWh, and the relatively low occupation of power plant sites. It is also suited to delivering substantial amounts of low-carbon baseload and uninterruptable demand.

In an innovation scenario, there is widespread usage of micro-reactors and small modular reactors. These innovative designs benefit from standardized factory construction and economies of scale. In such a scenario, modelling indicates a modest increase of nuclear power capacity in the energy supply at the expense of renewable energy such as offshore wind. There is also a significant reduction in installed power generation capacity as nuclear is more effective at supplying baseload than variable renewable energy and reduces the requirements for large-scale electricity storage.

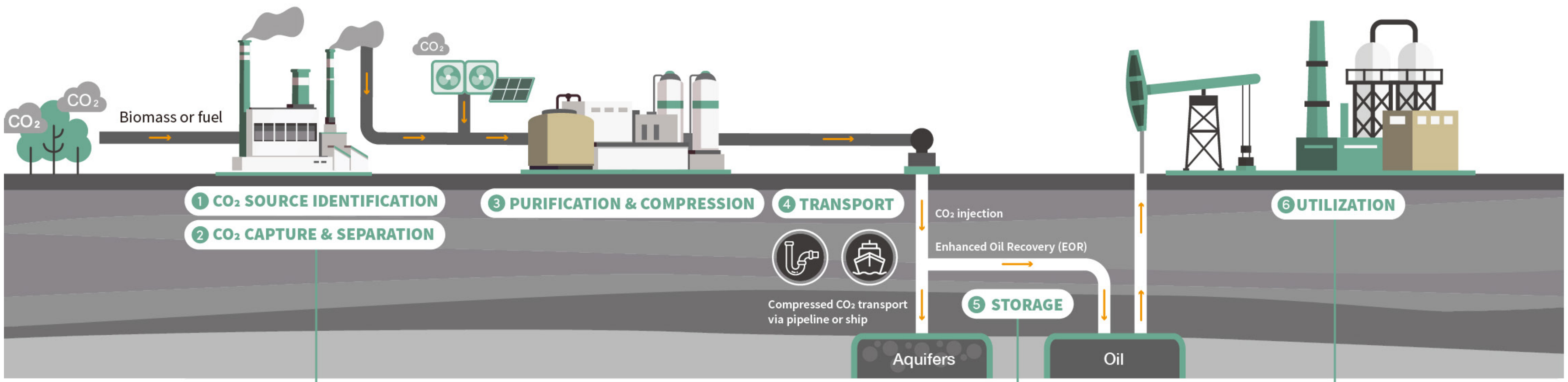
FIGURE 27

**Installed Electricity Generation Capacity** [GW] **Carbon Neutrality Innovation Scenario**



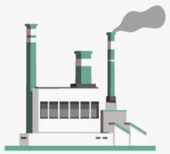
# CARBON CAPTURE, USE AND STORAGE (CCUS)

CCUS is essential to unlock the full potential of decarbonization and attain carbon neutrality



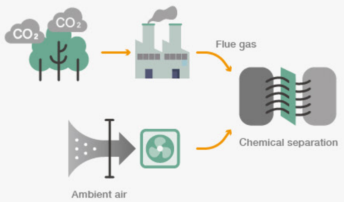

## Point Sources of $CO_2$ in Industry

$CO_2$ from industries (cement, steel), hydrogen production from fossil fuels, or power generation is captured before it reaches the atmosphere and is then compressed and injected into porous rock layers.



## Biomass Energy with Carbon Capture and Storage (BECCS)

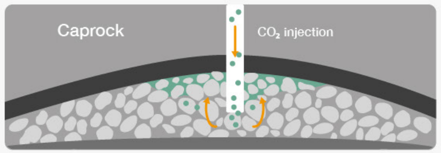
## Direct Air Carbon Capture and Storage (DACCS)




Net negative emissions technologies are key to reach net-zero and then net negative emissions. In BECCS, $CO_2$ is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, $CO_2$ is captured directly from the air.

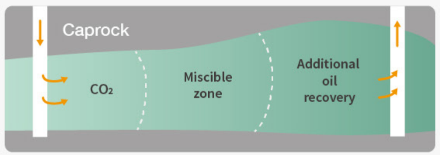
## Aquifers for Sequestration of $CO_2$

Aquifers are geological formations containing brine in porous rock at depths over 1km. $CO_2$ can be pumped down into the rock for sequestration.

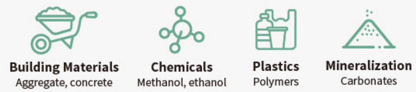



## Enhanced Oil Recovery (EOR)

EOR is a family of techniques that increases the recovery of oil and gas while storing $CO_2$. Dependent on operational choices, the volume of $CO_2$ stored could exceed the $CO_2$ content of the produced hydrocarbons.




## Solutions for Carbon Utilization




Carbon utilization can unlock the commerciality of CCUS projects for the industrial, steel, cement and chemical sectors. $CO_2$ captured can be used as a feedstock to produce a range of products, such as concrete, methanol, ethanol, carbonates, plastics etc.

**Awareness**
Recognise CCUS as a viable climate mitigation option and consider it when developing national plans.

**Acceptance**
Develop and integrate policies to allow full commercialisation of CCUS technologies.

**Finance**
Create a funding mechanism for CCUS and direct investments towards modernization of energy infrastructure.

Designed by Shuyue Li

## Carbon capture, use, and storage

**Carbon capture, use, and storage (CCUS) technologies are essential to mitigate climate change.** However, the public perception and acceptance of CCUS are still low across the UNECE region. Ideally, CCUS should be avoided, but practically it cannot be excluded as an option because it is one of the few disposal techniques that remove atmospheric carbon in meaningful quantities. If society cannot restructure fast enough, it is a potential last-resort technology.

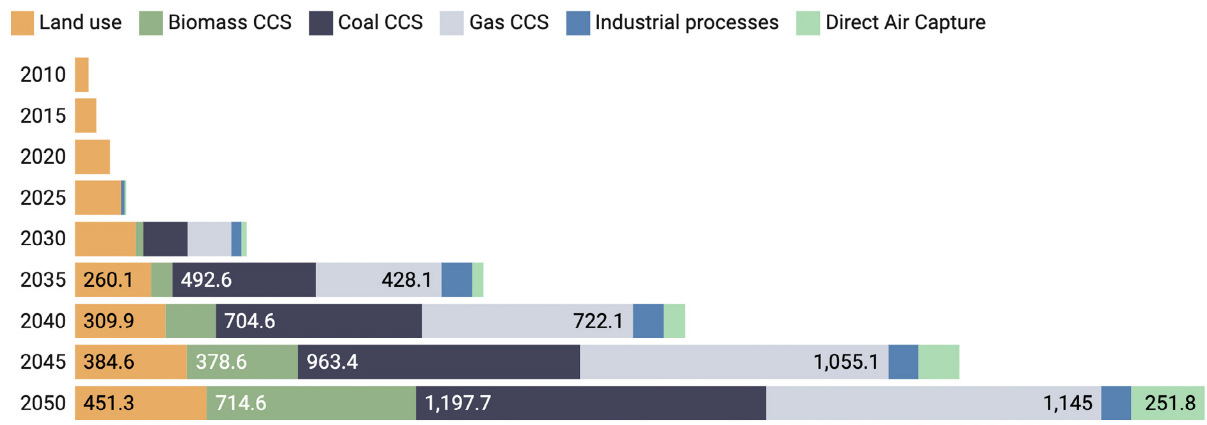
**CCUS has the potential to establish a pathway to carbon neutrality and meet emission targets** while mitigating the social and economic downsides of a rapid phase-out of fossil fuels. It is also essential for energy-intensive industries that cannot decarbonize easily. Today most CCUS is financed using enhanced oil recovery (EOR). In the future, the amount of $CO_2$ that needs to be sequestrated will be vast – at least 2.2 billion tonnes per year. CCUS needs to be funded as a $CO_2$ disposal technology into, for example, saline aquifers or as a solution for a circular carbon economy. This requires an environmental taxation approach to finance CCUS.

**Carbon capture technologies are typically installed at point sources such as fossil-fueled power plants and polluting factories in this innovation scenario**. As fossil fuels phase-out, suitable sources decrease. There is also further development of Biomass Energy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DAC).

**CCUS at point sources will not capture all emissions**. Increasing the proportion of captured $CO_2$ increases both capital and operational costs in power plants and industries. There are also emissions from the use of fossil fuels in transport which have not been decarbonized. So, attaining complete carbon neutrality means that all fossil fuel plants with CCUS installed and all transport emissions need to be matched with negative emissions capacities such as BECCS or DAC. DAC must be given full parity with other CCUS technologies. DAC is a robust carbon sequestration solution as it provides genuinely permanent storage, unlike most land use, and does not rely on natural resources, unlike BECCS and land use.

FIGURE 28

**Carbon Capture and Storage by Technology Carbon Neutrality Innovation Scenario** [$MtCO_2$/yr.]




**In the Carbon Neutrality scenario, CCUS plays an essential role**. In a CCUS priority scenario for Carbon Neutrality, CCUS means that natural gas usage remains constant while oil and coal decrease, but not to the low levels seen in other carbon neutrality scenarios. In this scenario, the UNECE region needs to install about three billion tonnes/year of CCUS capacity by 2050.

**CCUS is a last-resort solution that adds flexibility for residual and hard-to-abate essential industries such as cement, steel, and chemicals.** It should not be seen as a way to preserve the use of fossil fuels. In the last decade, costs have plummeted for wind and solar, which makes them lower cost than fossil fuels. However, not all activities, including energy-intensive industries, can be decarbonized easily. CCUS has struggled with cost overruns and disappointing results at test facilities and needs significant policy support.

## Is carbon capture essential to attain carbon neutrality?

Low-carbon energy supply technologies and lifestyle changes are not enough to limit global warming well below 1.5-2°C compared to the pre-industrial level. Therefore, societies understand that capturing and storing $CO_2$ will be a necessity. $CO_2$ needs to be actively removed from the atmosphere.

Different options are explored, including an accelerated penetration of CCUS and DAC. While some schools of thought believe that the possibility of removing $CO_2$ from the air will decrease the urgency of a non-fossil fuel-based energy system, it is essential to note that without the deployment of all CCUS technologies, the UNECE region will not be able to attain carbon neutrality and the Paris Agreement targets.

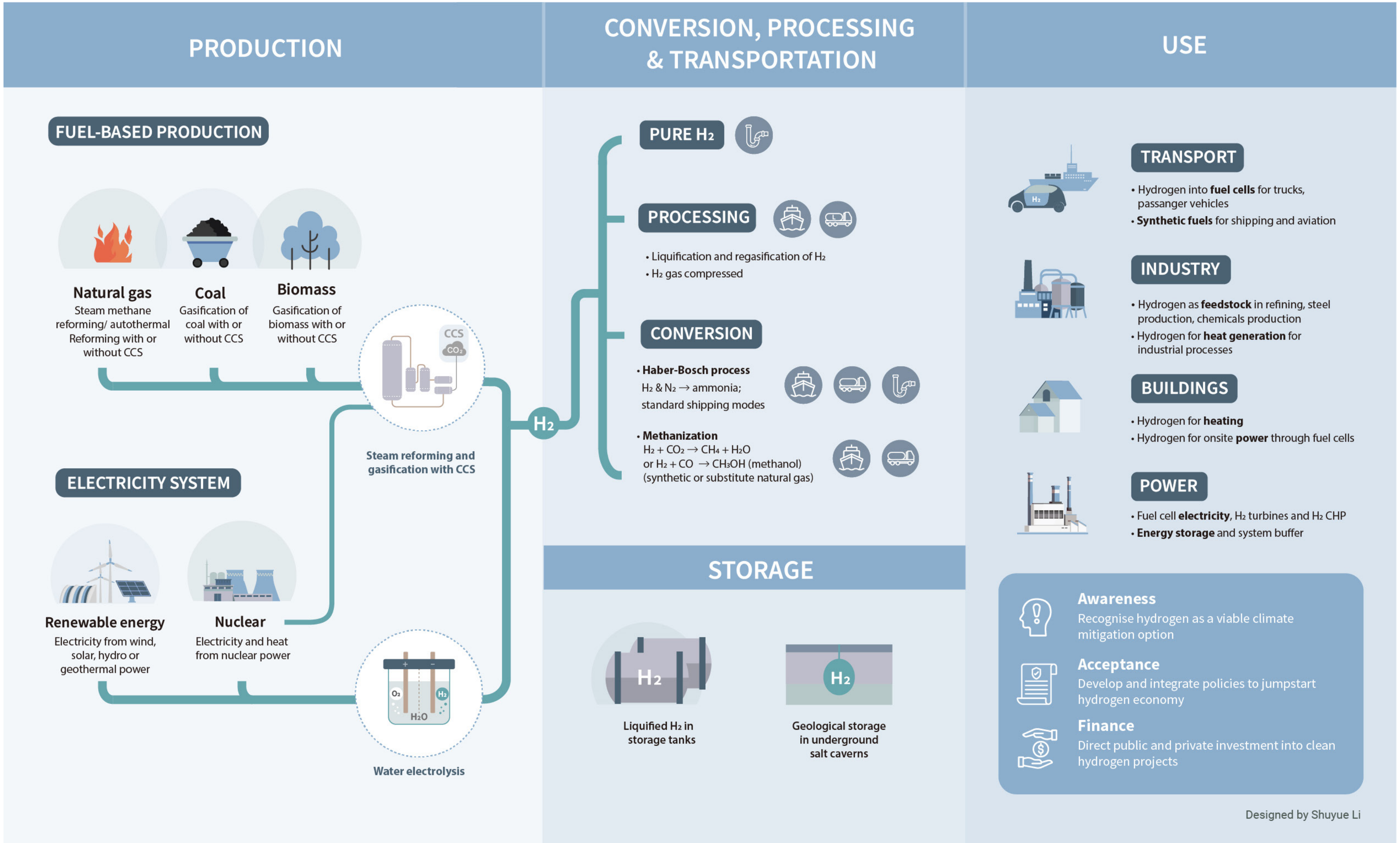
In the carbon neutrality innovation scenario, DAC sees an exponential increase due to faster technology learning and market penetration. It requires energy input and incurs costs. DAC costs money, and unlike CCUS at power plants, there is no source of revenue to cover the cost. Despite enabling a higher and longer-lasting presence of fossil fuels in the energy system, DAC has numerous invaluable indirect social impacts on the feasibility and ease of the energy transition to carbon neutrality, from reducing the need for variable renewable generation, electricity storage, and nuclear power.

## What happens to fossil fuel use in the future?

A broader sustainable energy system aims to keep fossil fuels in the ground. However, fundamental transformational change in energy systems takes time. Many critical sectors of the economy are hard to decarbonize. By retrofitting fossil fuel plants with carbon capture and subsurface storage technologies, we can mitigate the effect of the fossil fuel industry. In 2050, fossil fuels will account for a smaller share of the overall energy mix. Outside of the energy system, substantial hard-to-decarbonize industries, such as the production of cement, steel, and chemicals, will still need fossil fuels, although at significantly reduced volumes and converted with $CO_2$ control measures.

# HYDROGEN VALUE CHAIN

Hydrogen, an innovative solution for achieving carbon neutrality



# Hydrogen

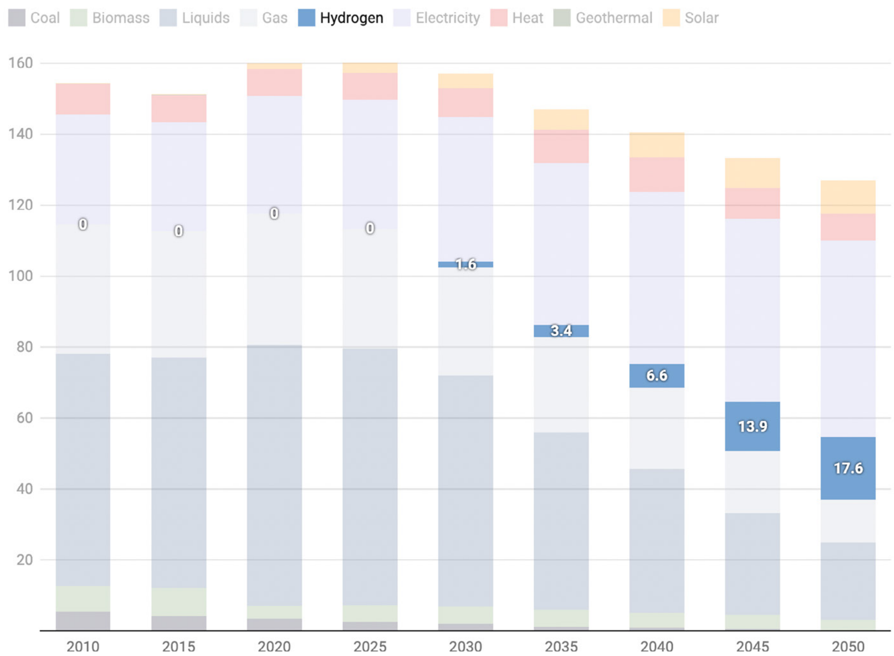
**Hydrogen is an innovative solution for achieving carbon neutrality and decarbonizing hard-to-abate sectors.** Sustainable hydrogen has been proposed as a backbone of a modern, decarbonized energy society. Hydrogen is already used as a chemical feedstock; for example, ammonia is used in fertilizers or hydrocarbons used for plastics. In the future, hydrogen can be used as an energy carrier and energy storage medium. It has vast, viable applications across various sectors that need to be decarbonized, such as transport, industry, power generation, and heat for buildings. It does, however, have disadvantages which make its adoption less than straightforward. It is hard to transport, difficult to store in large quantities, represents an explosion hazard and has an indirect global warming potential (GWP) if allowed to escape to the atmosphere.  The economics of production depends on the price of resources required to produce hydrogen, such as natural gas, coal, or renewable and nuclear power electricity.

**The carbon-neutral innovation scenario models the potential hydrogen-based economy.** This includes hydrogen electrolysis with solid oxide electrolyzers, which can operate with high-temperature heat from nuclear power. Moreover, the hydrogen to fuel pathway is modelled, including hydrogen-to-methane, hydrogen-to-methanol, and other liquid fuels. This assumes that hydrogen can be used to make liquid synthetic fuels that can, for example, replace gasoline used in different sectors. In this scenario, the increase of hydrogen usage by citizens in heating buildings and powering transport assumes increased government support and incentives.

**Hydrogen can progress the decarbonization of hard-to-abate sectors, such as energy-intensive industries using high temperatures in their processes or long-haul transport.** These are examples of crucial economic activity where electrification of end-use is only partially possible or the technology does not yet exist. Hence a rapid shift to a "hydrogen ecosystem" is consistent with the aims for carbon neutrality by 2050 and the Agenda 2030 for Sustainable Development. It requires a deliberate, swift, and extensive expansion of renewable and low-carbon hydrogen production.

FIGURE 29

**Total Final Energy Supply** [EJ] **Carbon Neutrality Innovation Scenario – Focus on Hydrogen**

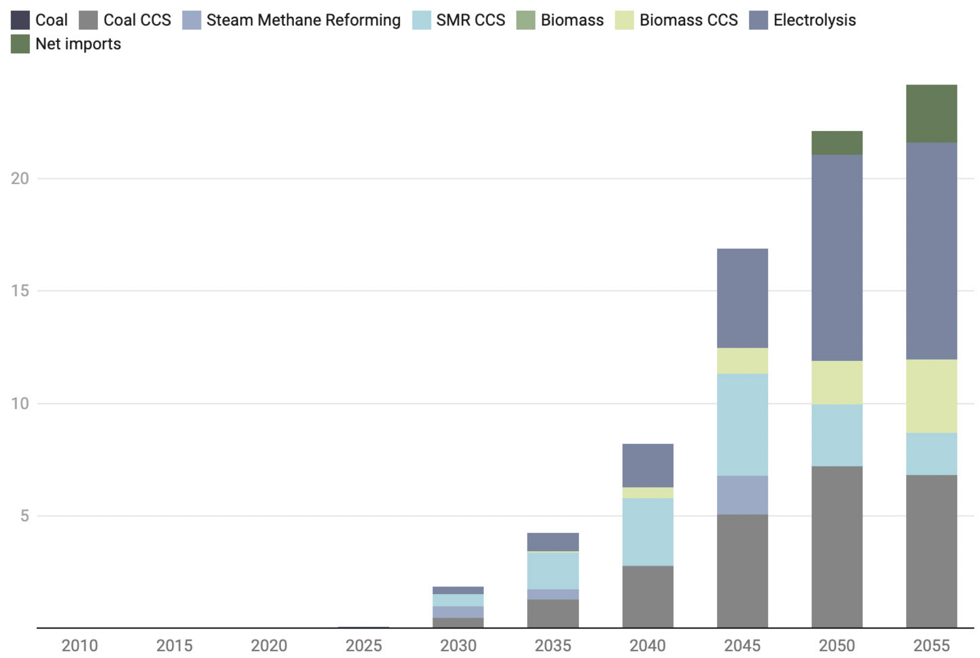


**To make a hydrogen economy a reality, governments should increase their efforts to decarbonize the energy sector.** Provided with adequate economic and financial capital incentives, the model scenario shows hydrogen electrolysis becomes a significant contributor to energy systems to use cheap and abundant electricity from low carbon sources, such as variable renewable energy and nuclear power. In the future, energy-importing countries can import hydrogen from a more comprehensive set of producers. Existing infrastructure, such as natural gas transportation and distribution, is assumed to be adaptable to help the transition to hydrogen. The support from the government for R&D and end-use adoption helps create niche markets for hydrogen-based technologies such as fuel cells.

**The challenge of expanding sustainable hydrogen production quickly means that policymakers should consider all sustainable hydrogen production options.** These include low-carbon sources, such as fossil fuels with CCUS, biomass with CCUS, and renewable energy and nuclear energy for electrolysis or thermochemical water splitting via high-temperature processes.

**FIGURE 30**

**Hydrogen Supply by Source** [EJ] **in Carbon Neutrality Innovation Scenario**




**A massive increase of sustainable hydrogen electrolyzers connected to the electricity grid means low- and zero-carbon electricity stations are needed to supply the increased demand.** Critical raw materials are needed for certain types of electrolyzers including platinum, iridium and cobalt. Therefore, nuclear power, biomass, wind, and solar power see a notable increase in electricity supply. Hydrogen from fossil fuels with CCUS also plays a significant role, and the region will depend on hydrogen imports by 2050. This scenario also highlights the contribution of nuclear power in the generation of hydrogen from electrolysis and steam electrolysis from small modular nuclear reactors.

**There is a considerable increase in CCUS for hydrogen production from fossil fuels in an innovation scenario.** The chemical industry traditionally obtains hydrogen for chemical products from gas, oil, and coal. In the presence of CCUS and DAC, coal gasification, natural gas steam reforming, and electrolysis are expanding their contribution to hydrogen supply. These proven technologies can be used to build a hydrogen economy but require the deployment of CCUS or another route to stop carbon from being converted to $CO_2$ and emitted into the atmosphere.

## Will nations be able to import hydrogen like oil and gas by 2050?

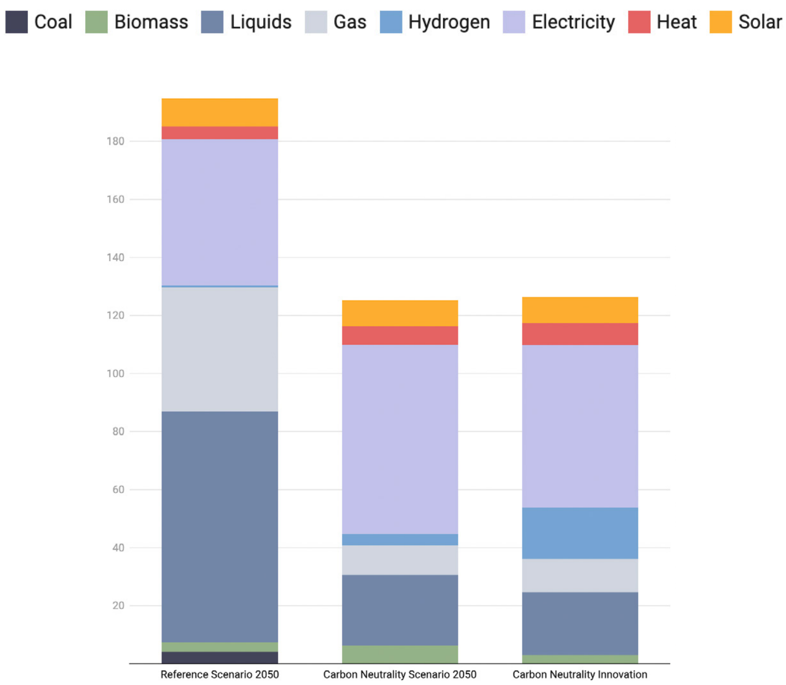
By 2050, a hydrogen priority model indicates imports of 1EJ per year of hydrogen. This is equivalent to nine million tonnes per year or ninety-four billion cubic meters (bcm)[5]. This is comparatively small when compared, for example, to the current European natural gas imports, which accounted for around 326 bcm in 2020. However, policymakers should be aware that only pipeline transportation of hydrogen is established. The large-scale transportation of liquefied hydrogen or hydrogen under high pressure remains a technical and economic challenge. Significant parts of the existing natural gas infrastructure will be repurposed to integrate hydrogen produced through electrolysis from low carbon sources (renewable energy and nuclear power) and hydrogen produced through natural gas with CCUS into the energy system.

5 Based on higher heating value - on lower heating value (LHV) it would be 8.4 million tonnes. The volume for LHV the volume then is 93.5 bcm at STP (standard temperature and pressure).

# TRUSTED TECHNOLOGIES OR INNOVATION?

FIGURE 31

**Total Final Energy Supply in 2050** [EJ] **Comparison of Scenarios**




Attaining resilient carbon neutral energy systems for the UNECE region would require the deployment of all low- and zero-carbon technologies across industrial, transport and buildings sectors. For the region to succeed in this endeavor, it would be important to:

- **Raise awareness and act on the potential** of all low- and zero-carbon technologies to deliver on carbon neutrality. This is possible through identifying and sharing approaches that have proven to successfully (and intrinsically) mobilize stakeholders to ensure widespread and decentralized uptake of the solutions suggested.
- **Develop a clear technology agnostic regulatory framework** and energy system design to allow all low- and zero-carbon technologies to be deployed into integrated carbon-neutral energy systems recognizing the considerable uncertainty inherent in the transition. Consistent policies and market frameworks across the region are necessary to provide favorable investment signals and attract private finance for high capital cost projects.
- **Design financing mechanisms and investment framework** that enables the deployment of all low- and zero-carbon technologies. Unlocking both private and public funding will require climate and sustainable finance classification based on scientific and technology-neutral methodologies that support the transition to a low-carbon economy.

# Industry

FIGURE 32

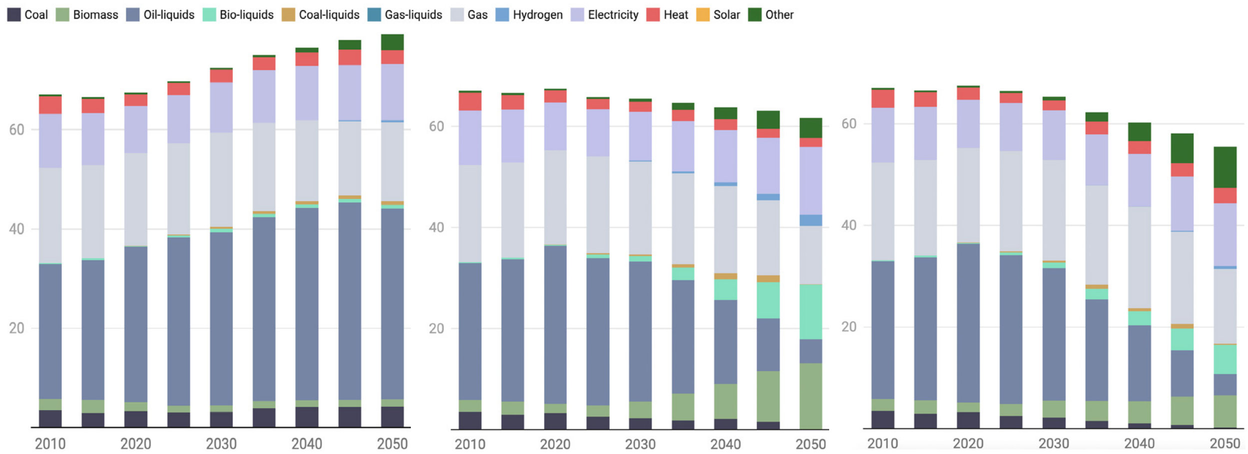
**Total Final Energy Supply** [EJ] **Industry Reference Scenario**

FIGURE 33

**Total Final Energy Supply** [EJ] **Industry Carbon Neutrality Scenario**

FIGURE 34

**Total Final Energy Supply** [EJ] **Industry Carbon Neutrality Innovation Scenario**




*Electricity is produced from various power sources, including fossil fuels and renewable energy.

**The decarbonization of industry is a top priority to attain carbon neutrality.** Energy-intensive industries are one of the principal GHG emitters, accounting for about 25% of total $CO_2$ emissions globally. Cement, iron and steel, and chemicals and petrochemicals industries are the most significant industrial $CO_2$ emitters, with shares in the sector reaching 27%, 25%, and 14%, respectively. Policymakers should verify that these industries are planning for the consequences of the decarbonization of energy because the supply of fuels and feedstocks to these industries is expected to be affected faster than the typical investment cycle of these industries.

**Energy-intensive industries are essential to support a low-carbon economy.** Among other uses, steel and concrete structures are required to support energy transition - for wind power, thermal insulation for energy efficiency, and lightweight materials for electric cars. Oil and natural gas will continue to be needed as fuel and feedstocks for these industries, as the decarbonization of vital processes will remain technically challenging. Industrial energy efficiency will be critical to reduce, substitute, and compensate for emissions through machinery replacement for higher efficiency, installation of heating control systems, and waste heat recovery.

**A variety of low- and zero-carbon technologies will support future industrial processes.** This includes deploying technology solutions for carbon-neutral industries by encouraging innovation and research and development to advance the development and deployment of all low- and zero-carbon technologies. Industrial energy efficiency, CCUS, hydrogen, nuclear power and heat, and electrification from renewable energy are vital to achieving a carbon-neutral industry sector.

**Industry will have to adapt to a diverse range of innovative energy options.** These include electricity, biomass, bio-liquids, vegetable seed oils, plastic waste recycling, and hydrogen. The development of policies for a circular economy is needed for this. Also, the deployment of CCUS technologies in the cement, fertilizer, chemical, and petrochemical sectors will be a crucial enabler for achieving carbon neutrality. Funding for methane reduction projects at coal mines is challenging to obtain and is dependent on carbon market finance. Any new coal-fired power projects should install CCUS and finance methane emissions reduction projects at mines that supply coal to industry.

**Establishing infrastructure, generation, and human capacities in pilot projects is urgent.** Projects could focus on hydrogen as a source of energy and process agent in industry, improving industrial processes' energy and material efficiency and increasing flexibility in energy demand by highlighting associated gains in resilience against energy and resource supply and price shocks. Actions will make companies more robust in a changing environment, simultaneously helping overall energy supply costs by avoiding/reducing peak load and thus indirectly assisting in levelling the grids.

**Clusters and the circular carbon economy can stimulate economies across the region.** The circular carbon economy that relies on carbon reduction, capture, reuse, and removal combined with an industrial cluster approach is a means of creating sustainable jobs, green products and industry competitiveness.

**Industry should prepare for significant changes in the supply chain.** Fossil fuels are the primary feedstock for industry. In general, industry requires an energy baseload. Any interruption of supply is likely to be disruptive. Industry can affect upstream energy projects that provide energy supply. Policymakers should prepare for sustainable and innovative technology interplay of all low- and zero-carbon technologies to run factories, support high-temperature processes, and remove $CO_2$ as by-products of industrial processes.

## Buildings

FIGURE 34

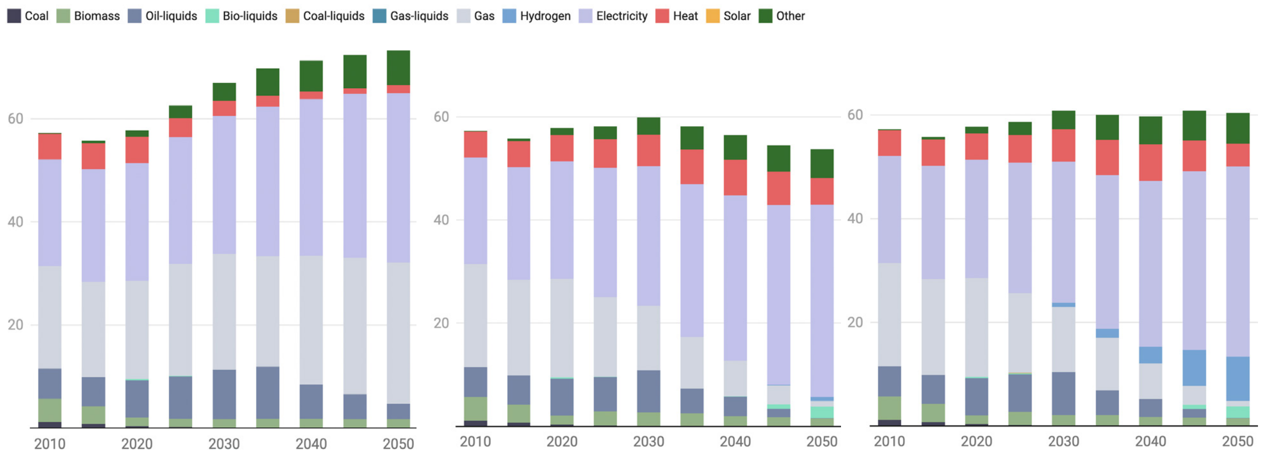
**Total Final Energy Supply** [EJ] **Buildings Reference Scenario**

FIGURE 35

**Total Final Energy Supply** [EJ] **Buildings Carbon Neutrality Scenario**

FIGURE 36

**Total Final Energy Supply** [EJ] **Buildings Carbon Neutrality Innovation Scenario**




**Residential and commercial sectors will require electrification at a scale and speed never seen before.** Most people in the UNECE region have their homes and businesses powered by natural gas and thermally generated electricity. Mass electrification will require a mix of policy options, including better grid efficiency to installing insulation and intelligent appliances.

**Improvements in energy efficiency in the building sector can make an immediate impact.** This includes decarbonizing buildings using enhanced retrofitting and insulation of existing infrastructure.

**Digital approaches could also identify efficient, effective, and economic transformative solutions.** The use of smart appliances, smart meters, leakage detection, and advanced load management techniques should be implemented to help detect energy usage anomalies and optimize energy use while establishing resilient energy systems that can automatically switch sources of energy depending on price and availability.

**Educational programs could also raise awareness of energy and resource consumption measures.** These include promoting reduced thermostat settings, encouraging heat pumps, and distributing renewable energy generation in households and public and commercial buildings.

**Hydrogen is expected to become a significant power and heat source for homes in many regions by 2050.** Deep electrification of the building sector is required for carbon neutrality. Renewable energy capacity and modern, energy-efficient appliances will also be required to see a dramatic increase. Hydrogen is expected to significantly penetrate the building sector in a carbon neutrality innovation scenario by 2050. It will mainly be used for heating homes as part of a system-wide digital transformation of the energy system.

**By 2050, natural gas, oil, and coal will be eliminated in servicing people's residential and commercial buildings' energy needs**. This is because of policy support for retrofitting buildings with insulation and improved energy efficiencies. Energy efficiency has excellent potential to reduce consumption, contribute to load profile management, and reduce infrastructure investment. This includes enhanced retrofitting and insulation of existing infrastructure and end-user education programs to raise awareness and promote reduced thermostat settings.

## Transport

FIGURE 37

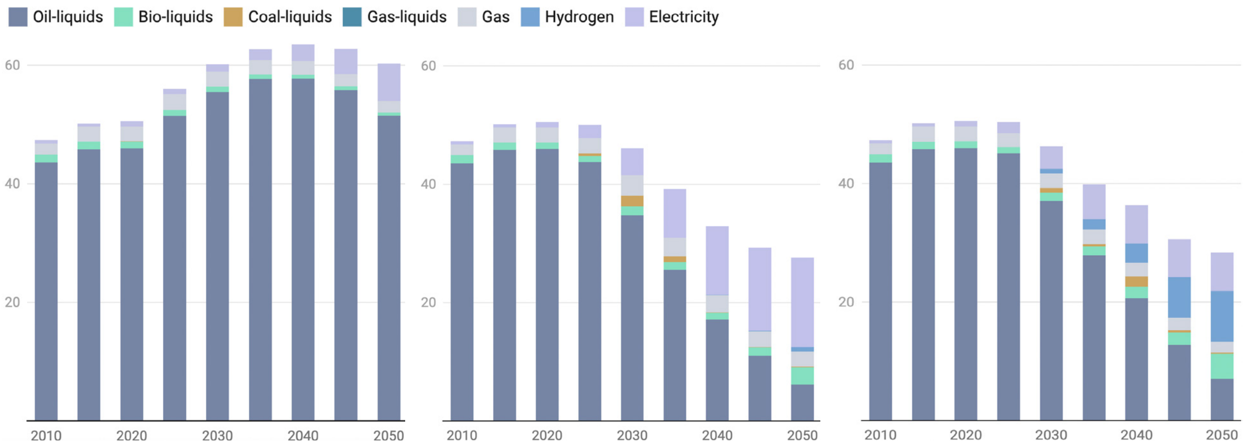
**Total Final Energy Supply** [EJ] **]**
**Transport Reference Scenario**

FIGURE 38

**Total Final Energy Supply** [EJ]
**Transport Carbon Neutrality Scenario**

FIGURE 39

**Total Final Energy Supply** [EJ] **Transport**
**Carbon Neutrality Innovation Scenario**




**The transport sector will experience profound structural changes.** Electric and hydrogen fuel cell cars, buses, trains, and other transport will need to become commonplace across the region. While there is a strong push for such an ambitious shift in the transport sector, it is essential to note that a lack of raw materials such as lithium and cobalt, as well as challenges associated with recyclability and the short life spans of electric car batteries, might hinder the complete electrification of a traditional urban car park.

**Current changes are nowhere near enough.** Transport across the region is dominated by oil liquids such as petrol and diesel. In recent years, transportation has modernized with an increase in electrified railways and the introduction of electric and hydrogen-powered vehicles. However, these have had a minor impact to date.

**Adequate policy support is needed for the market entry of new transport infrastructure.** To stimulate structural shifts to low-carbon fuels and technologies, emission taxes with the removal of diesel cars could be considered. Other policy measures include government support for electric charging stations and hydrogen stations and encouraging flexible working schedules, car-sharing, and increased uptake in public transport. Natural gas vehicles will also require policy support to see minor increases in usage alongside biofuels such as bioethanol and bio-diesel vehicles.

**There remain serious technology challenges to decarbonizing transport.** Although there will be improvements in transport efficiency, lifestyle changes will also be required. All freight transport by road, sea, and air continues to cause significant emissions. Rural areas will be the hardest to restructure compared to urban areas.

**Hydrogen and biomass play a role alongside electricity in decarbonizing transport.** Reducing oil demand and emissions is an absolute priority. Furthermore, hydrogen should be promoted for long-distance freight and passenger transport. Biofuel usage for mobility purposes should be considered interim if the global supply of corn and grains is not endangered. Biomass and waste are well-positioned as feedstock for biogas and upgraded biomethane production, ready to be injected into the gas grid for heavy-duty transportation.

**Electrification of transport will impose a significant burden on the public.** It requires that the public purchase the electric vehicle and adapt to the shorter range and long 'refueling' times. This is particularly challenging in poor and rural areas. Very cold and very hot regions pose their issues concerning battery performance. Efforts to persuade consumers to buy smaller cars and use less air conditioning would help reduce battery sizes.

**Electrification of transport requires a balanced policy stance.** The electrification of transport couples two previously unconnected markets, which are priced, taxed, and regulated separately – fuels and electricity. The electrification of transport will impact the overall electricity price if capacity is not increased in line with this extra demand. Tax revenues from fuels will also change. Carbon neutrality targets are typically based on deadlines to be net zero. However, climate change is determined simply by GHG emissions. The construction of electric vehicles brings $CO_2$ emissions forwards (due to battery production), assuming a similar vehicle usage pattern. Transport-related emissions will only reduce if the electricity comes from low carbon sources. Optimizing transport to limit climate change and ensuring stable, affordable energy markets will be complex.

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# ANNEX 1

The United Nations Framework Classification for Resources (UNFC) is a classification of projects where the projects aim to produce products for use. It is described in full in this reference.

The structure of UNFC is simple and follows the natural progression of projects starting with a study of the sources from which products may be produced and ending in two streams, one for products that will be sold or used outside the project and one for products that will be produced and used by the project or not used. Between these points, the projects are being prepared, first by collecting information on how they can fit within the environmental-and socio-economic constraints, and on how they can be shaped physically, and then by characterising the development, production, and decommissioning operations. Focusing on decisions made which are observable is simple. If straying into a discussion of what decisions should be made, on what grounds and how this becomes as complicated as real life and should be avoided for purposes of accounting of the status.

The metrics that projects carry are categorized with respect to the degree of confidence of the estimates. This is expressed as a range of uncertainty when physical observations are being used or as a degree of confidence in the reports examined when direct observations with a range of uncertainty are not available.

This basic structure reflects the characteristics of many project types. The UN Secretary-General has recommended that it be used for transforming extractive activities for sustainable development and has formed a Working Group on Transforming the Extractive Industries for Sustainable Development to work on this challenge. The Working Group is co-led by the five UN Regional Commissions on a rotating basis (UNECE is the lead Regional Commission in 2022) and the specialized agencies the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP).

**FIGURE 1**

**UNFC classes and sub-categories in a 3D presentation**

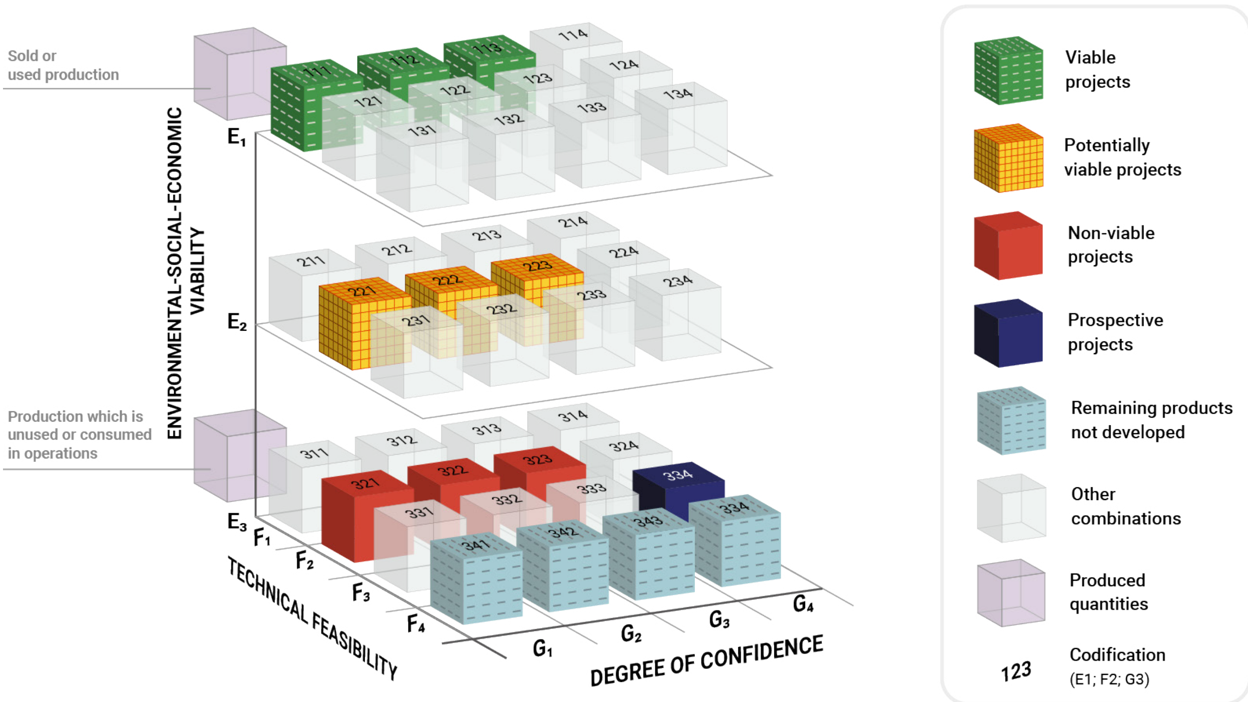
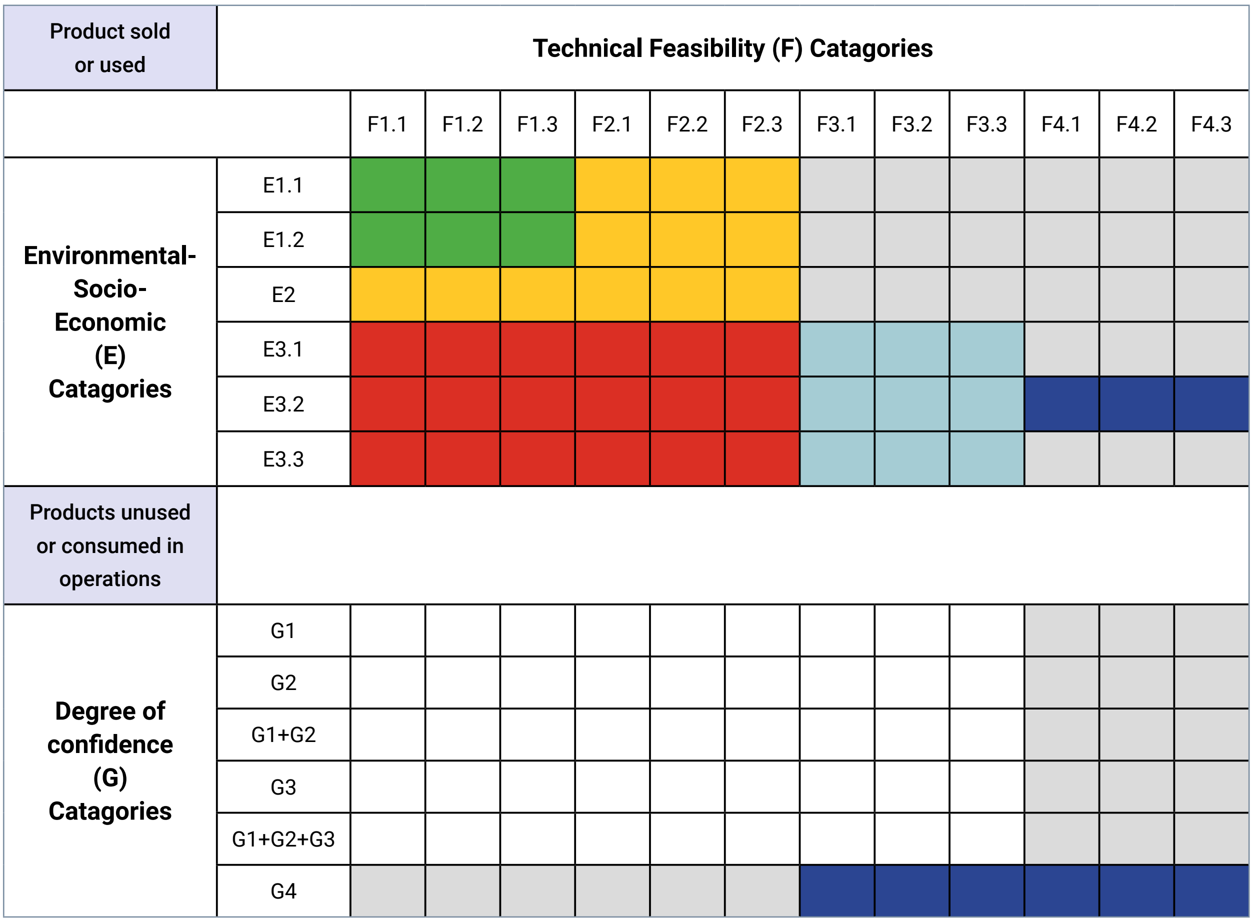


FIGURE 2

**UNFC in two-dimensional form**




The projects often go through many phases. To match these, subcategories are defined within both the E and the F categories, as shown in the 2-dimensional matrix defining the classes according to their E and F categories, the 1, i.e., E1 and F1 being the most mature stages, or for the metric the estimates with the highest confidence. The metrics that the projects carry (G categories) are referred to in the lower part of the matrix and will be entered in the E-F matrix.

The structure of UNFC is powerful, not only due to its simplicity that makes it applicable to a wide range of energy and mineral projects, but also because it identifies environmental-socio-economic categories in the classification reflecting these real-life contingencies. Both are necessary to integrate projects well in the complex and interconnected economies that continue to develop.

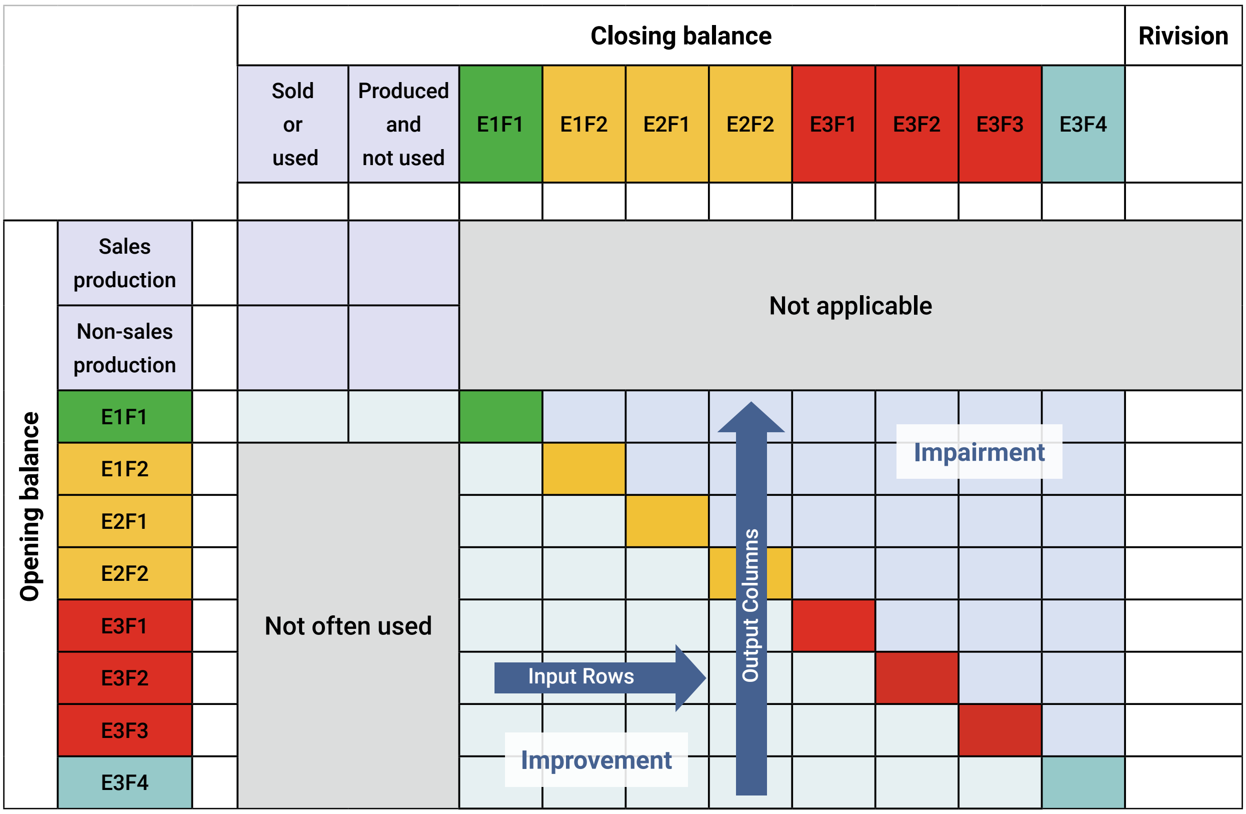
Recently, the United Nations Resource Management System (UNRMS), in complement to UNFC, has entered the specification and development process supporting the resource delivery aspects of meeting the 2030 Agenda for Sustainable Development. UNRMS is a voluntary global standard for integrated resource management within the framework of public, public-private and civil society partnerships that is uniformly applicable to all resources. For sustainable resource management to be holistic, i.e., respond to the complexity of all resources, time and space scales, and life cycles, it should be principles-based. UNRMS is based on twelve fundamental principles that provide general guidance on sustainable resource management's direction.

## The Resource Management Matrix

The Resource Management Matrix is another form of the two-dimensional representation of UNFC. It conforms with the Design Structure matrices used in the project and organizational management and the Input-Output tables used in econometric analyses for national statistics. The EF classes shown in figure 1 are here listed in identical order on both axes, with the most mature class at the top and to the left. Projects are shifted horizontally in their row from the opening balance to where it sits in the closing balance. The closing balance is found by aggregating values in the columns. Improvements will plot below the diagonal and impairments above, revealing at a glance if the year has been a good one or not.

**FIGURE 3**

**The resource management tracking changes from one period to the next**




*Note: Colour coding is as in Table 1.*

The Resource Management Matrix was first introduced in 2020, with a case study illustrating its use. It was then named the Resource Account. In 2021, it was extended to research applications for studying the effects of alternative policies or other conditions on the resource account.

The metrics addressed by the G-categories are traditionally quantities of sources and products, but they need not be limited to that. They can be other information carried by projects, both in scalar form and as a time series. Daily resource management is generally based on forecasts.

The resource management tool described above is a natural one, used by many in one form or another. Norway uses a particularly transparent scheme in its management of oil and gas resources that can be found on www.NPD.no. The website contains specifications of the detailed input requested by license operators. NPD quality controls the information for consistency with global constraints, and error results are reported to the inner and outer state bodies for Government decision support as well as in the form of aggregated scalars and forecasts of public interest to the public.

**Carbon neutrality in the UNECE region: Technology Interplay under the Carbon Neutrality Concept**

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