From Ambition to Implementation

NTNU and SINTEF's
Research-Based Advice

COP31 TÜRKİYE ANTALYA

NTNU SINTEF

ISBN 978-82-14-08550-1

Content

From Ambition to Implementation 4
Recommendations for This Year's Negotiations 5
A selection of global SINTEF and NTNU projects 6

1. Rapid Emissions Reductions 8
Short-Lived Climate Forcers 10
Long-Lived Greenhouse Gases: SF_6 and HFCs 11

2. Clean Energy 12
The Power Supply and the Energy System 14
Batteries 15
Solar 16
Onshore Wind 17
Offshore Wind 18
Hydropower 19
Bioenergy 20
Energy Security and Preparedness 21

3. Industrial Transition to Net Zero 22
Energy Efficiency in Industry 24
Hydrogen 25
Carbon Capture and Storage (CCS) 26

4. Carbon Dioxide Removal (CDR) 28
Three alternative technologies 30

5. Food, Materials and Circular Value Chains 32
Circular Bioeconomy 34
The Role of Food Systems 35
Circular Material Flows and Waste Management 36
Minerals and Critical Raw Materials 37

6. Climate-Resilient Societies 38
Climate-Neutral, Energy-Efficient Buildings and Cities 40
Maritime Transport 41
Sustainable Cooling 42

7. A Just Transition and Cooperation with the Global South 43

From Ambition to Implementation

Nils Røkke and Asgeir Tomasgard

The first Global Stocktake under the Paris Agreement sent a clear message: the world largely knows what it takes to cut emissions, and many of the technologies already exist. Yet the transition is moving too slowly.

Renewable power has grown rapidly and energy efficiency has improved, but the gap between climate targets and actual emissions remains wide. More and more people are gaining access to energy and better living conditions, and global energy demand is rising. Renewables must therefore meet new demand and replace fossil sources at the same time, which makes the transition harder.

Emissions must fall this decade, even as we adapt to the climate change already under way. That demands major changes in how we produce and use energy and resources. The longer we wait, the more expensive and difficult the transition becomes.

Research and innovation are essential, but technology alone does not cut emissions. Investment must be targeted at what works, and the resulting solutions must actually be deployed. Some technologies can be rolled out at scale today; others need further development and demonstration. We also need to get better at spreading solutions that already work. This requires capital, skills and policy instruments that reduce risk and speed up deployment.

For policymakers, then, the question of how to deploy technologies faster matters as much as the question of which technologies are needed. Policy must address climate, nature, energy security and competitiveness together. Measures that serve several of these goals at once are often easier to implement. But the goals can also pull in different directions, for example when they compete for grid capacity, power and land. Good decisions therefore depend on understanding the consequences of different choices and knowing which measures deliver the greatest overall benefit.

NTNU and SINTEF work closely with businesses and public authorities in Norway and internationally to develop and demonstrate energy and industrial solutions. Through this work, we see where technology is mature, where knowledge gaps remain, and which barriers stand in the way of faster implementation. Together, NTNU, Norway's largest university, and SINTEF, one of Europe's largest independent research institutes, have a broad strategic outlook. We see needs and solutions across sectors, and we see time horizons shrinking: solutions we once regarded as long-term are now needed within a few years.

COP31 should therefore be a summit for implementation. We know a great deal about what needs to be done, and many of the solutions exist. The task now is to move faster and put them to use. Saving the planet as we know it will pay off.

Recommendations for This Year's Negotiations

1. Accelerate emissions reductions this decade

Implementing the Paris Agreement requires measures that deliver rapid, measurable emissions reductions. Emissions of short-lived climate forcers such as methane, and of long-lived fluorinated greenhouse gases such as SF_6 and HFCs, must be cut alongside CO_2 emissions to limit near-term warming.

2. Speed up the transition to clean, resilient and accessible energy systems

Renewable energy deployment must go hand in hand with stronger power grids, energy storage, flexibility, energy efficiency and energy security measures. Technology development and system integration are essential to deliver both emissions reductions and security of supply.

3. Strengthen the industrial transition to net zero

Industry needs a predictable policy framework that encourages investment in energy efficiency, hydrogen, carbon capture and storage, and other low-emission solutions. Demonstration, scale-up and international cooperation must be given higher priority.

4. Develop solutions for durable carbon removal

Carbon removal will be needed in addition to deep emission cuts. Research, pilot projects and robust systems for measurement, reporting and verification must be prioritised so that removals deliver a real climate benefit and can be trusted.

5. Build circular, resource-efficient value chains

The green transition cannot be separated from resource use, the protection of nature, and security of supply. Key priorities include resource efficiency, waste prevention, circular material flows, the circular bioeconomy, sustainable food systems, and access to critical materials.

6. Invest in climate-resilient societies

Climate adaptation must be built more firmly into plans for energy, transport, buildings, and urban development. Societies must be equipped to cope with rising climate risk while continuing to cut emissions.

7. Strengthen a just transition and cooperation with the Global South

The green transition must create local value, build skills, and expand energy access. Partnerships of equals in research, education, technology development and innovation are essential if the transition is to succeed globally.

8. Make research, innovation and higher education an integral part of implementation

Political targets alone will not deliver the Paris Agreement. Research, technology development, innovation, and skills development must be recognised as essential to developing, deploying and scaling up the solutions needed.

A selection of global SINTEF and NTNU projects



1. Brazil, Spain and Canada

Project: InterOpt

SINTEF and NTNU, together with partners from Brazil, Spain and Canada, are developing optimisation models for the global renewable energy industry. InterOpt will research how machine learning methods can optimise the production of renewable energy across markets.

2. Nepal

Project: EnergizeNepal

For decades, researchers from NTNU and SINTEF have helped Nepalese authorities and professionals develop sustainable hydropower. EnergizeNepal is a competence-building project to scale up renewables in Nepal.

3. India

Project: INDEE+

INDEE+ aims to encourage the refrigeration and air conditioning sector in India to adopt more environmentally friendly technologies. NTNU leads the project and SINTEF is the research partner.

4. Southeast Asia

Project: OPTOCE

Through the project, SINTEF has contributed to reducing the inflow of plastic pollution into the world's oceans by establishing a circular value chain where plastic is collected and used as an input factor in the cement industry.

5. Tanzania, Ethiopia, Uganda, Mozambique, South Sudan, Malawi

Project: Energy Technology Network (NET)

Seven African universities are collaborating with NTNU through Norad's NORHED II programme to develop small-scale renewable energy solutions for off-grid use.

6. Kenya, Uganda, South Sudan

Project: Capacity building for socially just and sustainable energy transitions

NTNU, UiS, the University of Juba, Makerere University, and the Technical University of Kenya are building capacity and expertise through education, research, and dissemination to ensure that the workforce in East Africa has the knowledge and skills needed to implement and advocate for a just and sustainable energy transition.

7. Europe

Project: F-MAP

F-MAP is developing an open-source modelling tool to help industry and policymakers compare ways of cutting emissions of fluorinated gases (F-gases) from refrigeration, air conditioning and heat pumps. The project, led by SINTEF, will test the tool in case studies in four countries on three continents.

8. Europe

Project: MISSION

MISSION is an EU project that develops three SF6-free circuit breaker technologies for medium- and high-voltage applications. The project includes 12 partners from 9 European countries and is led by SINTEF.

9. China

Project: CHEERS

The EU project CHEERS, led by SINTEF, has helped build the world's largest green incineration plant (4 MW) utilising the chemical circulation combustion (CLC) method. CO_2 capture is a natural part of the combustion process and is therefore almost 70 per cent cheaper than other capture methods.

10. Africa

Project: OpenMod4Africa

The EU-funded project OpenMod4Africa, led by SINTEF, aims to foster sustainable, reliable, and competitive energy systems across Africa. It is expected to significantly influence the continent's future energy landscape. The project focuses on developing regional expertise and creating a set of open models and scenarios for long-term energy system development in 26 African countries.

1



Rapid Emissions Reductions

Why this matters

The green transition is about more than cutting emissions by 2050. Rapidly reducing the emissions that drive warming in the near-term matters just as much. The world is already experiencing rising temperatures, more frequent extreme weather, and significant impacts on nature, society, and the economy. Measures that can limit warming over the coming decades are therefore essential to keep the goals of the Paris Agreement within reach.

While CO_2 remains the main driver of long-term climate change, a range of other greenhouse gases and climate forcers have a far stronger warming effect per tonne emitted in the short term. Methane and other short-lived climate forcers, along with fluorinated gases such as SF_6 and HFCs, together account for a substantial share of today's warming. Existing technology, better regulation, and more effective monitoring can cut many of these emissions quickly. Acting on them will deliver measurable climate benefits sooner.

Success depends on stronger international cooperation. The key tools will be international standards, technology development, and better measurement, reporting, and verification of emissions. These emissions arise in many different sectors and value chains, but they share one feature: cutting them is among the fastest and most cost-effective options the world has for limiting warming between now and 2035.

Short-Lived Climate Forcers

NTNU: Anders Strømman
SINTEF: Julian Straus, Rahul Anantharaman, Gunhild Reigstad, Øyvind Skreiberg

Short-lived climate forcers (SLCFs) are gases and particles that stay in the atmosphere for anything from a few days to a few decades. Although their atmospheric lifetime is much shorter than that of CO_2, they account for a significant share of today's warming. Methane is the most important of them and alone accounts for around 0.5 °C of observed global warming[1]. Because methane breaks down faster than CO_2, cutting its emissions can deliver rapid climate benefits.

Some particles, such as sulphates and nitrates, cool the climate by reflecting sunlight. Others, such as black carbon (soot), cause warming, particularly when they settle on ice and snow and reduce how much sunlight the surface reflects. Gases such as methane (CH_4), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and carbon monoxide (CO) help form ground-level ozone (O_3), a potent greenhouse gas.

These emissions come from energy production, transport, industry, waste management, and the combustion of fossil and renewable fuels. For methane, the main sources are agriculture, waste, and fossil energy production. Cutting these emissions can bring quick gains for the climate, human health, and the environment, but realising them requires better knowledge of where emissions come from and what effects they have, as well as better monitoring.

The measures needed range from energy-efficient combustion and cleaner technology in transport and industry to better waste management and less use of fossil fuels. For methane, reducing leaks from oil and gas operations is one of the most cost-effective measures,[2] and much of this can be done with existing technology. Closing the knowledge gaps will take better monitoring and better data on where emissions come from and how they affect the climate and human health. Climate models also need to include both warming and cooling forcers to produce more accurate projections.

What should be done?

- Make the Global Methane Pledge binding and set a target of zero technical emissions.
- Reduce methane emissions from oil and gas through monitoring, reporting, and the use of Best Available Technology.
- Use taxes and regulation to make cutting emissions more profitable than emitting.
- Introduce clear requirements and measures to reduce anthropogenic emissions of SLCFs.
- Invest in research, monitoring systems, and climate models that include both warming and cooling forcers.
- Develop technology to abate methane from low-concentration sources.

Long-Lived Greenhouse Gases: SF_6 and HFCs

NTNU: Kaveh Niayesh, Frank Mauseth
SINTEF: Nina Støa-Aanensen, Petter Nekså, Kristina N. Widell

SF_6 (sulphur hexafluoride) is the most potent greenhouse gas known, with a global warming potential (GWP) 24,300[3] times that of CO_2 and an atmospheric lifetime of at least 1,000 years. SF_6 is used in almost all electrical switchgear (circuit breakers, gas-insulated switchgear, cable terminations, etc.) at distribution and transmission levels (medium and high voltage). As the world electrifies, the global power grid is expected to more than double in size by 2050[4]. If this expansion relies on today's technology, the amount of installed SF_6 could multiply, and emissions would rise accordingly. Atmospheric measurements show that both the total amount of SF_6 and annual emissions are increasing[5].

HFCs, another group of gases, can have GWP100 values of up to around 15,000, as in the case of HFC-23. These gases are widely used in air conditioning and heat pumps. Cutting emissions and switching to alternative gases can therefore make a major contribution to reducing climate impact in both the short and the long term.

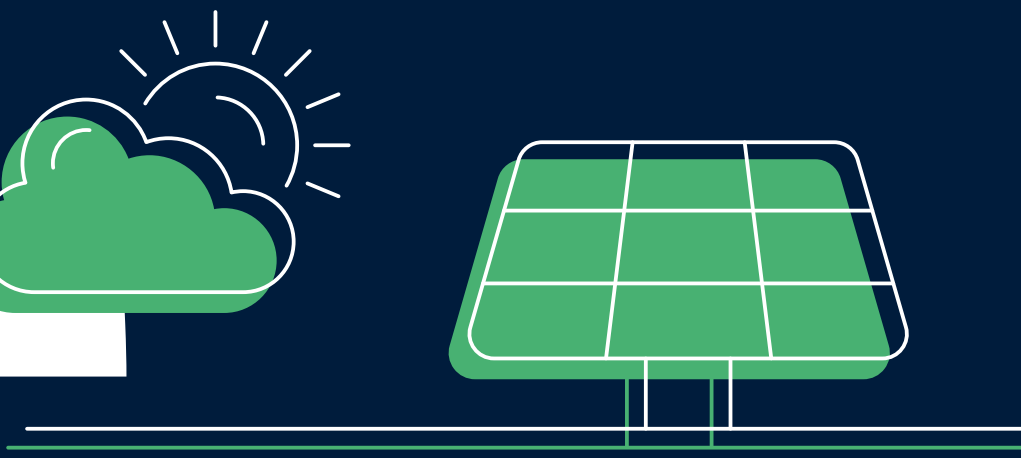
Electrical switchgear typically has a service life of 30–40 years, so it is important both to replace SF_6 in existing installations where possible and to stop new SF_6-based equipment from being installed. At the same time, alternative technologies must be shown to control the power grid safely. Research into using alternative gases in new switchgear, or to retrofill existing SF_6-filled equipment, is key to speeding up the SF_6 phase-out, alongside stronger global regulation of SF_6. A complete picture of SF_6 use and emissions also requires reporting from the defence industry and research into suitable alternatives for its applications.

HFCs are covered by the global Montreal Protocol, which originally controlled ozone-depleting gases. The Kigali Amendment to the Protocol, adopted ten years ago, provides for a gradual phase-down of these potent greenhouse gases. Alternative fluorinated gases with short atmospheric lifetimes, and therefore a low warming effect, have been developed. Developing technologies based on gases that occur naturally in the biosphere (natural refrigerants), and converting to them, is important. It is particularly important to help poorer, fast-growing countries with large cooling needs gain access to such technology.

What should be done

- Set a global timeline for removing SF_6 from new and existing electrical equipment.
- Introduce global reporting requirements and mandatory registration of SF_6 procurement, use and emissions in all sectors, defence included.
- Introduce a global ban on deliberate SF_6 releases from electrical equipment during operation, maintenance and decommissioning. Introduce harmonised global taxes.
- Step up research into new technologies that can replace SF_6 in electrical equipment at all voltage levels, including retrofill solutions.
- Require potent HFCs to be replaced with natural refrigerants that have no long-term environmental consequences. This should be done through the EU F-gas Regulation and forthcoming restrictions on PFAS emissions and use.
- Incentivise technology transfer and assistance that support the shift to natural refrigerants in low- and middle-income countries (LMICs).

2



Clean Energy

Why this matters

The green transition depends on rapid deployment of zero-emission energy. Meanwhile, electricity demand is rising as industry, transport and other parts of society are electrified. To meet the goals of the Paris Agreement, renewable power generation must increase substantially, and power supply and energy systems must become more flexible, resilient and efficient.

Solar, onshore wind, offshore wind, hydropower and bioenergy will play different but complementary roles in the energy systems of the future. A growing share of variable generation calls for investment in power grids, energy storage, flexibility and new energy carriers such as hydrogen. Integrating these solutions cost-effectively will be essential for both emissions reductions and energy security.

The energy transition is therefore not just a matter of generating more renewable energy. It is about building energy systems that can deliver secure, affordable and sustainable energy to communities worldwide.

The Power Supply and the Energy System

NTNU: Magnus Korpås, Pedro Crespo del Granado
SINTEF: Erlend Sandø Kiel, Maren Istad

As electrification increases, Europe and the rest of the world face major challenges in securing a resilient, flexible and sustainable power supply. The power grid will be the backbone of the future energy system. Connecting large volumes of renewable and distributed generation will require substantial investment and modernisation. So will meeting new electricity demand as industry, transport and other sectors electrify to cut their greenhouse gas emissions.

Renewable energy sources, digitalisation and new players such as flexibility providers and local energy communities are making the global energy system more complex. Delays in grid development and a lack of grid capacity could slow the transition to a low-emission society and put climate targets at risk. Taken together, new threats and stresses, greater complexity, uncertainty and unpredictability mean the energy system needs to become more resilient.

The solution lies in a smarter, more flexible and more robust power grid. Digitalisation and automation make it possible to monitor and control the grid in real time. With sensors, data-driven decision systems and artificial intelligence, we can optimise operation, prevent faults and increase capacity without major physical expansion. We also need to develop sustainable grid components, such as switchgear, cables and transformers, that can cope with renewable generation, battery charging and more extreme weather. These components must be manufactured using fewer critical raw materials.

What should be done?

- Invest in smart grids and make use of flexibility in generation, consumption and energy storage. Prioritise research and development on digital and automated solutions, and on using flexibility to increase capacity quickly while reducing environmental impact.
- Move towards more flexible, risk-based grid operation that makes fuller use of capacity and strikes a better balance between security of supply and cost.
- Incentivise consumers, producers and local communities to contribute local generation and flexibility to the grid.
- Develop regulations and price signals that reflect real costs, distribute those costs fairly and encourage better use of the grid.
- Ensure reliable interfaces between the power grid and other parts of the energy system.

Batteries

NTNU: Odne Stokke Burheim, Ann Mari Svensson
SINTEF: Fride Vullum-Bruer, Ingeborg Kaus, Paul Inge Dahl

Batteries are a key technology in the transition to a low-emission society and a prerequisite for a resilient and flexible energy system. Investment in batteries and energy storage is higher today than ever before, driven by the need to electrify transport, integrate more renewable energy and strengthen energy security. Batteries support zero-emission transport and help balance the power system by storing energy when wind and solar output is high and supplying electricity when demand peaks. According to COP29 estimates, global battery capacity must increase sixfold between 2022 and 2030 to support electrification[6].

Batteries also play an increasingly important role in civil protection and emergency preparedness. They can keep critical infrastructure supplied with power during outages, strengthen local energy systems and reduce the power system's vulnerability. In addition, batteries are used for frequency regulation and peak-shaving, which can reduce the need for grid expansion, particularly where capacity is limited. In low- and middle-income countries, batteries will be essential for energy storage in microgrids, providing access to stable and reliable energy.

Research and development must be prioritised to improve today's lithium-ion (Li-ion) technology and to develop next-generation batteries, such as sodium-ion, solid-state and recyclable systems. New technologies must be safer, less resource-intensive and based on readily available, non-critical raw materials.

Europe has sought to build a competitive battery industry, but progress has been slow: costs are high, regulatory processes are lengthy, and Asian manufacturers undercut European producers on price. For Europe to build a strategic battery value chain that strengthens the green transition, industrial competitiveness and preparedness, it needs faster permitting, a stable policy framework, and targeted incentives. Closer cooperation between research institutions, industry and authorities, at both national and Nordic levels, can help build a competitive and sustainable battery sector in line with the EU's green industrial strategy.

What should be done?

- Reduce batteries' carbon footprint by introducing global requirements for low-emission production and minimal impact on nature across the entire battery value chain.
- Prioritise more sustainable Li-ion solutions, new battery chemistries and technologies, and better recycling.
- Establish certification schemes for climate and environmental footprint, material origin and recycled content.
- Simplify permitting and financing schemes so that new companies can start production sooner.
- Strengthen incentives and instruments for joint research and industrial projects.
- Recognise batteries as critical infrastructure for the energy transition, energy security and civil preparedness.

Solar

NTNU: Steve Völler
SINTEF: Gaute Stokkan

Solar energy is growing rapidly worldwide and now attracts more investment than any other form of new power generation. The technology is scalable, affordable and flexible, but the sector needs sustainable solutions, efficient land use and more regional value chains. Global investment in solar photovoltaics (PV) now exceeds investment in all other generation technologies combined[7], and solar PV is expected to become the largest contributor to renewable electricity by 2028[8]. Like all renewable energy, solar PV needs a lot of land. It is currently estimated that 2.2 % of Europe's total land area could be used for solar and wind energy production, and rooftop solar accounts for only 0.2 % of this[9]. Rapid scale-up of solar power could therefore lead to land-use conflicts.

The technology has large material demands, and as older solar panels are retired, the volume of waste will grow. This makes circularity and recycling essential for a sustainable value chain. Securing local manufacturing capacity is an important political and security objective, to prevent individual countries or regions from gaining a monopoly. A stronger European value chain that makes use of national and regional strengths will be key to building a sustainable and resilient solar energy sector.

Silicon is likely to remain the main material in solar cells for the foreseeable future, but higher efficiency and new applications will depend on further research into tandem solar cells, which combine silicon with other materials. Solar panels must also be designed for recyclability, so that their materials can be reused and the environmental impact reduced.

Alongside energy storage and grid measures, the sector needs digital solutions that can predict variations in supply from different types of solar installations, so that these can be integrated as effectively as possible. Artificial intelligence will be an important tool here.

What should be done?

- Use legislation and incentives to accelerate the roll-out of rooftop and building-integrated solar panels.
- Develop dual-use solar installations (for example, combining solar power and agriculture) to reduce land-use conflicts.
- Design panels for recyclability and build a circular value chain for solar.
- Rebuild the European solar industry to reduce dependencies and the global dominance of individual countries.
- Establish common incentives and standards across countries.
- Develop storage solutions, digital control systems and forecasting tools.
- Prioritise the development of silicon-based tandem cells for higher efficiency.

Onshore Wind

NTNU: Trond Kvamsdal,
SINTEF: Gard Hansen, Konstanze Kölle,
Markus Peter First

Onshore wind can deliver large amounts of renewable power quickly and cost-effectively. A sufficient power supply is essential for emissions reductions, electrification and industrial development. In many countries, onshore wind is central to the energy transition and to energy security, and the technology already accounts for a significant share of the world's renewable power generation[10]. However, development, operation and decommissioning must take account of nature, land use, local communities and a changing power system. Increasing electrification of industry, transport and the petroleum sector is driving demand for more power and greater flexibility. At the same time, geopolitical instability and more vulnerable supply chains are making access to components, spare parts and digital services less certain.

Land and nature are scarce resources. Stricter requirements on biodiversity, emissions and land use, combined with growing conflict over licence applications, can delay or halt projects. This calls for policy instruments and processes that build public acceptance and reduce conflict (stakeholder involvement, licensing processes, compensation and financing schemes). If onshore wind is to contribute to the energy transition on the scale required, it must be developed in ways that protect both nature and local interests. This requires better planning, targeted mitigation measures and solutions for restoring and reusing land.

Because wind farms depend on monitoring, data collection and remote operation, digitalisation and cybersecurity are becoming an integral part of how land use and nature are managed. Digital solutions provide better knowledge of impacts on nature and wildlife, more efficient operation and better use of existing facilities.

Upgrading existing wind farms can deliver more power with less environmental impact than new development. Upgrades require less new land, increase efficiency and make use of existing infrastructure. Upgrading depends on technology development to extend component lifetimes and ensure their reliability, and on access to data.

What should be done

- Introduce land-use planning and project design that balance techno-economic interests, social factors and nature.
- Create incentives to extend the lifetime and improve the reliability of components in wind farm operation (including cables, cable joints, substations/transformers and other "weak links") and of wind turbine components (access to data and damage information from manufacturers).
- Establish system integration and grid connections that reduce vulnerability (power transmission, bottlenecks, interaction with the wider power system).
- Prioritise decommissioning and circularity in onshore wind (dismantling, reuse and recycling, and requirements and schemes for site restoration).

Offshore Wind

NTNU: Trond Kvamsdal, Michael Muskulus, Erin Bachynski-Polić
SINTEF: Gard Hansen, Konstanze Kölle, Hagbart Skage Alsos

Offshore wind has very large global potential and could become a cornerstone of the future renewable energy system. The technology can produce large amounts of emission-free power, but it requires a predictable framework, industrial development and close cooperation between the authorities, research and industry. Offshore wind currently accounts for a small share of global wind power capacity, but its technical potential is many times greater than today's global electricity consumption[11]. Offshore wind farms can be built close to major population and industrial centres, and often involve fewer conflicts and less environmental impact than onshore wind.

Floating offshore wind is still at an early stage of development and costs more than fixed-bottom technology, but its potential is large: around 80 % of the world's offshore wind resources are in waters too deep for anything but floating solutions. Costs will fall through learning, innovation and scale-up once conditions are in place to build more floating wind. Realising the plans for offshore wind also requires adapting the power system. New transmission infrastructure must be built, both offshore and onshore, so that offshore wind can be integrated with other renewable sources such as hydropower, and with storage technologies like batteries and hydrogen.

Meeting offshore wind targets will require a stronger and more comprehensive commitment to research, innovation and education. Knowledge, new technology, efficient solutions and a workforce with the right skills are key success factors. Leading European research institutions, working with major industrial companies, have identified two research areas as particularly important[12]: floating offshore wind and the large-scale grid integration of offshore wind power. Their vision is for offshore wind to become a backbone of the future energy system, developed with respect for nature and society, and delivering prosperity through clean and affordable energy for all.

What should be done

- Hold annual licensing rounds for new offshore wind areas to give industry a stable, predictable framework.
- Include commitments to research, development and to building skills and expertise, in licensing and support schemes.
- Require developers to make the data they collect available for research and further technology development.
- Build out grid connections both offshore and onshore so that offshore wind can be integrated efficiently with hydropower, hydrogen and other renewable energy and storage.
- Establish a framework for long-term investment in essential infrastructure such as ports, cables and service vessels.
- Expand the North Seas Energy Cooperation (NSEC) to coordinate the development of offshore wind and associated offshore grids.

Hydropower

NTNU: Tor Haakon Bakken, Leif Lia
SINTEF: Atle Harby

Hydropower is the world's largest source of renewable energy, and its role in future energy systems will continue to grow. As more wind and solar power is built, the need for flexible, dispatchable energy increases. Many hydropower plants in Europe and North America are ageing and were built to older standards. They need extensive upgrading and modernisation to keep them running, make them more flexible and improve their environmental performance. New developments must also be weighed against the protection of nature and local communities.

No renewable technology other than hydropower combines this degree of flexibility and dispatchability with large storage capacity at an acceptable cost. As power grids shift on a large scale from fossil sources to wind and solar, they will need far more balancing and energy storage, on time scales ranging from seconds to days, weeks and seasons. Providing this will require grid analysis, adapted market designs and optimised operational planning.

Pumped storage hydropower currently accounts for 94 % of all energy storage in power grids, with more than 200 GW of installed capacity. That capacity could grow considerably: the International Hydropower Association's 2025 World Hydropower Outlook reports more than 600 GW of pumped storage under development. Options include retrofitting pumped storage to existing reservoirs, building new reservoirs, reusing old mines, using the sea as the lower reservoir and other innovative solutions. Pumped storage can provide services ranging from black start and frequency regulation to storing water and energy over days and weeks. Adding it to existing reservoirs must not worsen environmental conditions. Pumped storage also needs a sound regulatory framework, so that projects that benefit society are carried out in a way that balances land use and local interests.

Together, these measures will make hydropower more sustainable and increase public acceptance. Modernisation can substantially increase installed capacity, allow more flexible operation and make better use of energy storage. It must also include environmental measures such as two-way fish migration systems, ecological flow releases and other measures to improve the ecological status of regulated rivers. Hydropower reservoirs and regulated watercourses can also help meet a growing need for other services that benefit society, such as flood control, irrigation, water supply, navigation and recreation.

What should be done?

- Develop solutions that provide more dispatchable power and greater energy storage while improving environmental conditions.
- Modernise existing plants and convert them to pumped storage to strengthen storage and system balancing.
- Invest in research on turbines, control systems and digital operation.
- Document impacts on ecosystems, develop modern environmental measures and build them into upgrade projects.
- Strengthen and demonstrate hydropower's role in providing other services to society, such as flood control, water supply and recreation.
- Introduce regulations and pricing mechanisms that reward flexibility and storage.

Bioenergy

NTNU: Marcos D.B. Watanabe, Raquel S. Jorge
SINTEF: Kathrin Weber, Øyvind, Skreiberg, Michaël Becidan, Judit Sandquist, Morten Seljeskog

Bioenergy is a key yet underutilised part of the transition to a renewable energy system. It can replace fossil raw materials in the chemical industry, supply carbon for metal production, and help cut emissions in transport sectors that are hard to electrify, such as aviation and long-distance shipping.

Through district heating, local heating and wood-burning stoves, bioenergy can ease the load on the power system, diversify energy sources, and strengthen energy security. Bioenergy is also central to developing carbon dioxide removal (CDR) technologies, which are becoming increasingly important for limiting global warming. Combining bioenergy with carbon capture and storage (BECCS) has the potential to deliver negative emissions at scale, through the utilisation of renewable biomass resources to permanently remove CO_2 from the atmosphere.

Biochar also plays a crucial role in the green metal industry, where it can replace fossil carbon in reduction processes for producing silicon, manganese, titanium and chromium. Building sustainable supply chains for biochar will strengthen security of supply, reduce emissions and safeguard industrial jobs in Europe.

What should be done

- Establish strategies for modern bioenergy that recognises its role in the energy transition, carbon dioxide removal (CDR), and emergency preparedness.
- Enable local use of waste and side streams (tops and branches, recovered wood, fish sludge, etc.) rather than exporting them, through incentives, regulation and better logistics.
- Expand district heating and other bioenergy solutions to relieve the power grid and reduce vulnerability in heat supply.
- Step up research on bioenergy, including the use of digitalisation and artificial intelligence to optimise value chains.
- Develop industrial production of sustainable biofuels (including sustainable aviation fuel (SAF) and renewable, low-carbon fuels for maritime transport) and bio-based chemicals as a basis for new value creation and stronger national preparedness.

Energy Security and Preparedness

NTNU: Magnus Korpås
SINTEF: Erlend Sandø Kiel

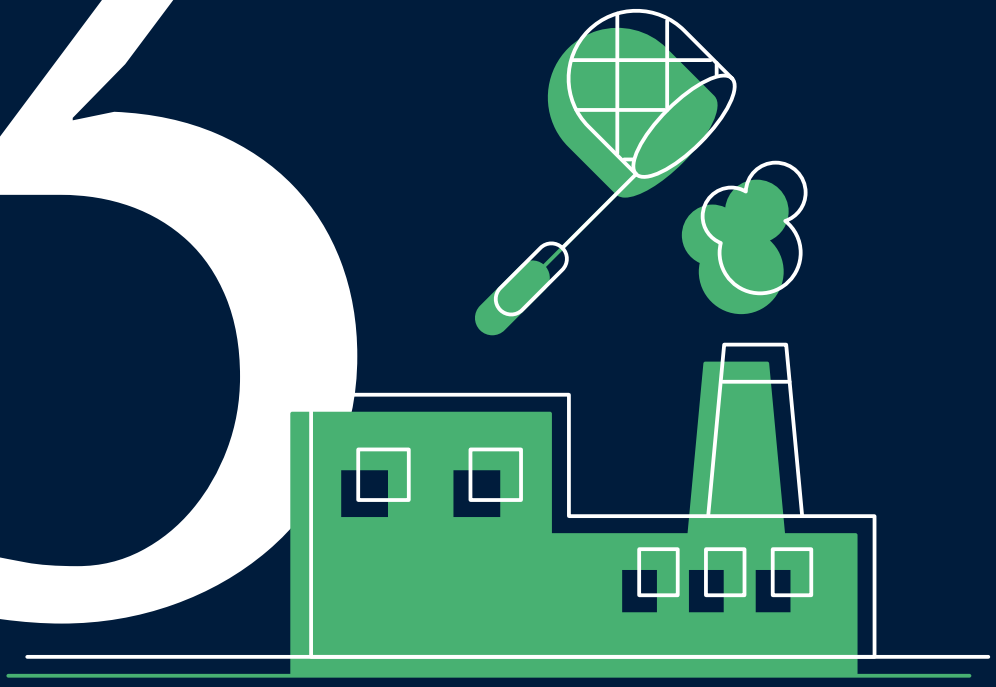
The energy system is central both to everyday life and to national defence and civil preparedness, not least through its interdependencies with road, rail, aviation, water supply, and communications infrastructure. It has traditionally been developed with a focus on cost-effectiveness and security of supply, and more recently on climate and nature. In the past, a resilient energy system mostly meant one that could cope with human error or with component failures caused by weather events. Planning now has to account for deliberate attacks as well, and for priorities that can reinforce or conflict with one another. A more efficient power grid, for example, can be harder to protect against deliberate attacks and more complex to operate. In other cases, priorities align: decentralised solutions based on renewable energy can make the energy system more resilient.

As attention turns to acute and visible threats, climate- and nature-related risks should not be sidelined. These risks are growing alongside the more immediate threats and could trigger or worsen humanitarian, political, and economic crises across regions. Building integrated, decarbonised energy systems that cut emissions and make society more resilient is therefore more important than ever.

What should be done

- Increase investment in research on physical and digital energy infrastructure, autonomous and distributed energy systems, and the interplay between civilian and military needs.
- Determine how threats such as hybrid attacks, sabotage, terrorism, and, in the worst case, war should shape the way energy systems are designed and operated. Many measures against deliberate threats also make systems more resilient to unintentional events such as natural disasters and accidents.
- Identify how disruptions in one sector can cascade to others, and how such knock-on effects can be anticipated, prevented, and limited in a crisis.
- Establish emergency repair capability and practise restoring energy supply after different types of incidents. Run scenario exercises with other sectors, including scenarios that rely on decentralised solutions.
- Build up stocks of critical equipment and secure access to supply and value chains and to technological resources, both nationally and through strategic partnerships. Map dependencies on foreign suppliers and assess the scope for producing critical equipment domestically.
- Build expertise in risk and resilience analysis of integrated energy systems, so that preparedness measures secure energy supply to critical societal functions.

3



Industrial Transition to Net Zero

Why this matters

Industry accounts for a significant share of global energy use and greenhouse gas emissions, while also producing the materials and products that society depends on. To move to a low-emission society, industry must therefore both cut its own emissions and develop new solutions that enable emissions reductions in other sectors.

Many industrial processes are hard to electrify, and often no single technology can solve the problem on its own. A competitive, low-emission industry will instead need several building blocks: energy efficiency, carbon capture and storage, alternative feedstocks, and circular carbon flows.

Industry is also vital for value creation, jobs, and economic development. A successful industrial transition must therefore combine emissions reductions with innovation, competitiveness, and sustainable use of resources. This requires a predictable, long-term policy and economic framework, because industrial investments tie up capital for decades. Without such a framework and safeguards against carbon leakage, companies are unlikely to invest in the green transition and may move production to regions with weaker climate regulation.

Energy Efficiency in Industry

NTNU: Armin Hafner, Thomas Alan Adams II
SINTEF: Petter Røkke, Petter Nekså, Kristina N. Widell

Improving energy efficiency is the first and most important measure in any decarbonisation strategy. The cleanest and cheapest energy is the energy that never has to be produced. More efficient industrial production and new ways of recovering surplus energy are among the most important steps we can take to help industry make better use of energy resources and reduce its climate footprint, in Norway and internationally. The growth in digital processing and artificial intelligence has led to a sharp rise in the number of new data centres. These use large amounts of electricity, and virtually all of it ends up as low-temperature excess heat. Around the world, stand-alone gas-fired power plants are being built to supply these facilities; they emit large volumes of greenhouse gases, and their excess heat goes unused.

Making better use of excess heat brings both business and societal benefits, particularly as so many new data centres are being built. However, many energy-efficient technologies have high development and investment costs. Industry therefore needs economic incentives that make it profitable to choose long-term solutions over short-term gains. Realising the potential we know exists will also require continued investment in research, innovation, and industrial projects that develop energy-efficient processes, components, and systems, as well as circular-economy solutions. These include industrial clusters, heat pump technologies, and heat-to-power processes.

What should be done?

- Require industry to identify and prioritise measures that improve energy use or save energy. This applies especially to new industry, which should be located with a view to integrating it into the energy system so that its excess heat can be used.
- Update and apply proven energy efficiency solutions across sectors.
- Take advantage of opportunities to exchange energy and material flows when establishing and developing industrial clusters.
- Support the adoption of new technologies and processes in Norway that improve efficiency and cut emissions, and help develop and transfer technology to low- and middle-income countries (LMICs).
- Enable low-emission and energy-efficient technologies to compete with fossil alternatives, and create a level playing field for different energy carriers (electricity and heat).
- Prioritise research and development of new technologies and components for more efficient resource use, such as high-temperature heat pumps that can replace fossil fuels for process heat, and heat recovery integrated with CCS.
- Develop strategies for climate-neutral industry through close cooperation between research institutions, businesses, authorities, and energy companies.

Hydrogen

NTNU: Frode Seland
SINTEF: Nils Røkke, Steffen Møller-Holst, Kyrre Sundseth, Stefania Gardarsdottir

Hydrogen is currently used in industrial processes such as ammonia and fertiliser production, refining and chemical manufacturing. In the future, hydrogen can help cut emissions in sectors that are hard to electrify, including metal production, other high-temperature industrial processes, and parts of the transport sector.

To make the transition to a renewable energy future, we must both introduce hydrogen into new sectors and decarbonise today's hydrogen production. Most of the world's hydrogen is produced from fossil sources, which generates substantial CO_2 emissions. Hydrogen could become key to lowering CO_2 emissions if we establish a framework that makes it competitive with fossil alternatives. That framework requires carbon pricing, regulation and support schemes to create demand.

As the share of wind and solar power grows, hydrogen will become essential for storing surplus energy and maintaining a stable energy supply when renewable output fluctuates. Hydrogen can also deliver major gains through sector integration, where production, storage and use are concentrated in geographical clusters, known as "hydrogen valleys". These valleys create economies of scale, cut costs and boost competitiveness.

Strict requirements on emission intensity will ensure that hydrogen develops in step with renewable energy and does not become a new source of emissions. Meeting them requires coordinated efforts between governments, industry and research communities, along with clear priorities and requirements for profitability and sustainability.

What should be done?

- Use carbon pricing and regulation to make polluting more expensive, while strengthening support schemes for scaling up zero-emission hydrogen production.
- Work towards a common international classification of hydrogen based on life cycle analyses (LCA). This would provide a transparent and comparable basis for trade and investment.
- Establish transitional schemes, including public funding, that drive scale-up and demand in the early market phase. Remove regulatory barriers and support the development of national and international markets and geographic ecosystems, such as hydrogen valleys.
- Incentivise the use of Best Available Technology in the extraction, transport and use of natural gas and hydrogen to minimise climate impacts.
- Strengthen cooperation with countries seeking rapid hydrogen deployment through bilateral trade agreements, combined with research and technology-neutral exchange.
- Implement border adjustment mechanisms such as the Carbon Border Adjustment Mechanism (CBAM) to safeguard the competitiveness of decarbonised industry and prevent carbon leakage to regions with weaker emission requirements.
- Prioritise developing cost- and energy-efficient electrolysis technologies, alternative low-carbon production technologies, and new solutions for transport, storage and end use, while ensuring safety and sustainability across the entire value chain.

Carbon Capture and Storage (CCS)

NTNU: Philip Ringrose
SINTEF: Mona Mølnvik

CCS covers the technologies used to capture CO_2, transport it, and store it safely in geological formations. According to the Intergovernmental Panel on Climate Change (IPCC), CCS features in almost every scenario for meeting the climate goals of the Paris Agreement. It is the only technology capable of decarbonising certain industries, such as cement and lime production and waste-to-energy, and it will be essential for reaching net-zero emissions by 2050 in other hard-to-abate sectors such as aluminium.

CCS is also indispensable for producing clean hydrogen from natural gas, known as blue or low-carbon hydrogen. Permanent CO_2 storage can help build hydrogen infrastructure cost-effectively, which in turn will support the transition to a renewable energy future. CCS can also be used for post-combustion capture at gas-fired power plants. It also lays the groundwork for CO_2 removal technologies, including bioenergy with CCS (BECCS), direct air capture (DAC) and direct ocean capture (DOC).

For CCS to help slow climate change, large volumes of CO_2 must be transported and stored every year by 2050. Achieving this requires standards based on both an understanding of how CO_2 mixtures behave throughout the CCS chain, and predictability to enable the CO_2 to flow through a network of different operators and across national borders. Policymakers must strike the best possible balance between regulation and market forces, and research-based evidence will be crucial.

What should be done?

- Deploy CCS in sectors that cannot be decarbonised by other means within a reasonable timeframe.
- Define “unabated fossil fuels” clearly, with requirements for rapid abatement and high capture rates based on Best Available Technology.
- Include emissions from process industries and fossil feedstocks, not just fuels, in the phase-out of unabated emissions.
- Require countries with large fossil resources to also offer CO_2 storage in line with the emissions they export.
- Develop international standards for cross-border CO_2 transport and storage to enable scale-up.
- Strengthen cooperation between industry, research and public financing to accelerate scale-up.





Carbon Dioxide Removal (CDR)

Why this matters

Even with extensive emissions reductions, some sectors will still produce emissions that are difficult or impossible to eliminate entirely. Reaching net-zero emissions and stabilising atmospheric greenhouse gas concentrations will therefore require removing CO_2 from the atmosphere and storing the carbon safely and permanently. Carbon dioxide removal (CDR) is not the same as carbon capture and storage (CCS)[13]; CCS prevents new fossil emissions from reaching the atmosphere, whereas CDR removes CO_2 that has already been emitted.

CDR covers both nature-based and technological solutions. According to the Intergovernmental Panel on Climate Change (IPCC), meeting the goals of the Paris Agreement will require removing large quantities of CO_2. However, many of the technologies are still at an early stage, and lack methods for measurement, reporting and verification (MRV). We must therefore develop solutions that are effective, sustainable and socio-economically sound. CDR may be needed to deal with hard-to-abate emissions, but it must not replace emissions reductions where emissions can be avoided or captured at the source. Cutting emissions must remain the primary strategy.

CDR does not yet have a clearly defined place in the climate negotiations. The Parties should clarify what role it should play alongside emissions reductions, and the UN should take the lead in ensuring that it develops sustainably and fairly. This requires a shared understanding of what emissions count as residual emissions. Countries should set separate quantitative targets for CDR in their Nationally Determined Contributions (NDCs)[14], distinct from their emissions reduction targets, and covering both nature-based and technological solutions. Funding for research, innovation and deployment must increase, and countries with higher historical emissions should bear a greater share of the costs.

Three alternative technologies

NTNU: Philip Ringrose
SINTEF: Kristin Jordal, Jorunn Skjermo, Kathrin Weber

Three technologies stand out as particularly relevant[15], although they differ in maturity, cost and scalability. Since 2026, all three have been covered by the EU's regulatory framework for certifying permanent carbon removals (CRCF).

Biochar

Biochar is a carbon-rich material where most of the carbon is locked into a stable structure. It is produced by heating biomass in an oxygen-free environment (pyrolysis). When biochar is added to soil or incorporated into materials such as concrete or asphalt, the carbon can remain stored for hundreds to thousands of years. The technology is commercially available, and biochar currently accounts for most of the delivered, verified carbon removal credits on the voluntary markets.

Biochar also offers other benefits: healthier soils, lower nitrous oxide emissions from agriculture, improved water and nutrient retention, and a production process that can be a source of renewable heat. The main constraint is the availability of sustainable biomass. Biochar can also replace fossil carbon in the metallurgical industry, but the carbon is then released again as CO_2, so it does not count as carbon removal unless the emissions are captured and stored (CCS).

What should be done?

- Support the development and use of biochar for carbon removal in applications that keep the carbon stored, such as soil, concrete and asphalt.
- Distinguish clearly in MRV between biochar for carbon storage and biochar for fossil carbon replacement in industry. When biochar replaces fossil carbon, the carbon is released again. This represents a reduction in fossil emissions, not carbon removal, unless CCS is used.
- Prioritise residues and waste as feedstock, in line with the cascading use principle.

BioCCS
(Capture and Storage of Biogenic CO_2)

Biogenic CO_2 capture and storage (bioCCS) captures CO_2 from the combustion or conversion of biomass, for example, at waste-to-energy plants, bioenergy plants, and industrial facilities that use biogenic carbon. The term largely overlaps with **bioenergy with carbon capture and storage (BECCS)**, but covers the capture of all sources of biogenic CO_2. The captured CO_2 is then sent for permanent geological storage, just as with CCS on fossil CO_2. However, because the carbon in biomass was originally drawn from the atmosphere through photo-synthesis, storing it results in net removal.

BioCCS uses far less energy per tonne of CO_2 removed than direct air capture (DAC), and the technology is ready for full-scale deployment. For example, from 2029, Hafslund Celsio will capture and store both biogenic and fossil CO_2. Capture plants require thorough flue gas cleaning, so bioCCS can also reduce emissions of sulphur oxides, nitrogen oxides and particulate matter. At the same time, CCS projects are expensive and can take many years to deliver. Biomass is in demand across many sectors, and according to the cascading use principle, should not be burned for energy if it can deliver greater value elsewhere.

What should be done?

- Introduce economic instruments that provide predictable payment for removed CO_2, and increase funding to realise costly bioCCS projects with long lead times.
- Facilitate cross-border CO_2 transport and storage.
- Establish bioenergy strategies that account for its role in carbon removal, and prioritise bioCCS from biomass that has no higher-value use, in line with the cascading use principle.

DACCS
(Direct Air Capture and Storage)

In direct air capture and storage (DACCS), CO_2 is captured directly from the air and stored permanently. The technology was developed solely for carbon removal, and its main advantage is that it does not require any biomass. The drawback is that CO_2 concentrations in air are very low compared with industrial flue gases, which makes the process far more energy intensive and expensive than capture from point sources, as with traditional CO_2 capture and storage (CCS) or capture and storage of biogenic CO_2 emissions (bioCCS). DACCS also needs more land per tonne of CO_2 captured than industrial capture.

A few plants are in operation, and more are under development. Europe's largest plants are in Iceland, with design capacities of 4,000 and 36,000 tonnes of CO_2 per year. DACCS is best suited to locations with abundant renewable energy and easy access to storage. At present, its only source of revenue is the sale of carbon removal credits on the voluntary market.

What should be done?

- Increase funding for research and innovation that reduces energy use and costs.
- Allow carbon removals from DACCS to be sold in regulated markets, so that plants no longer depend solely on the voluntary market.
- Build DACCS primarily where renewable energy is abundant and CO_2 storage is easily accessible.

5



Food, Materials and Circular Value Chains

Why this matters

How we produce, use, and reuse resources has major consequences for the climate, nature, and food security. Today's linear value chains generate substantial emissions and large volumes of waste, and they make inefficient use of biological and industrial resources. Moving to more circular systems is therefore an important part of the green transition.

Food production, bioresources, and access to critical raw materials will all be essential to the societies of the future. Demand is also growing for solutions that cut food waste, make better use of residual resources, and get more value from the resources already in circulation.

A more circular economy can cut emissions, strengthen security of supply, and create new industrial value. Achieving this requires technology, policy, and markets to work together, along with new forms of collaboration across sectors and value chains.

Circular Bioeconomy

NTNU: Anita Romsdal
SINTEF: Ida Aursand, Ana K Carvajal

A circular bioeconomy makes better use of biological resources and creates value with a smaller climate footprint. Resources from agriculture, forestry and the ocean are the basis for our food, materials and energy, and demand for them will grow as fossil raw materials are phased out. Bio-based materials and chemicals can also replace fossil feedstocks in industry and cut emissions in sectors that are hard to electrify.

Moving to a circular bioeconomy requires a systemic shift in which technology, regulation, markets and collaboration develop in parallel. Digital tools for mapping and sharing resources can help make industrial symbiosis a reality, but they must be combined with functioning markets, efficient logistics, and a clear policy framework. Profitability and climate benefits also depend on where, when and in what quantities resources arise, and on how they can be collected, stored, transported and used.

A shift of this kind calls for coordination across sectors and levels of government. Public authorities must develop a more coordinated policy for the circular bioeconomy, with industrial, climate, agricultural and fisheries policy all pulling in the same direction. National targets for circularity should be set, along with indicators that measure resource efficiency and value creation. Markets for secondary raw materials and biological by-products must also be built up, and demand for them stimulated.

Integrated testbeds and demonstration projects can link technology, markets, regulation and logistics in practice. By developing such ecosystems, Nordic and European countries can share their experience internationally and help find global solutions for sustainable resource use. A more circular bioeconomy will not only reduce waste and emissions, but also strengthen food security, value creation, and the green transition, showing how economic growth can go hand in hand with lasting emissions reductions.

What should be done?

- Promote collaboration between sectors such as aquaculture, agriculture, industry and energy to make better use of by-products and residual streams.
- Build digital and physical infrastructure, including platforms, standards and logistics solutions, that enables sharing and efficient circular resource flows.
- Adapt legislation and incentives to enable the safe and profitable use, transport and trade of biological by-products, and help the establishment and scale-up of industrial symbioses.
- Strengthen research and innovation in the circular bioeconomy, including biotechnology, material recycling, circular logistics, value chain development and business models that make circularity profitable.
- Establish test arenas where technology, markets and regulation are developed together, and share the lessons learned across borders.

The Role of Food Systems

NTNU: Eva Falch
SINTEF: Ida Aursand, Kristina N. Widell

The greatest challenge facing the global food system is producing enough food for everyone. Food production also competes with other uses for land, water, and energy, and the food system accounts for around a third of global greenhouse gas emissions. Food systems depend on natural resources that are highly vulnerable to climate change, yet food production has itself changed ecosystems profoundly: it accounts for 70 % of global water withdrawals and is a major driver of deforestation and biodiversity loss. Food that is produced but never eaten uses land, water, and energy without feeding anyone, and organic waste sent to landfills releases methane, a greenhouse gas with a strong short-term warming effect. The food system is therefore central to both emissions reductions and climate adaptation.

Solutions will require expertise from many disciplines, along with enabling technologies, new processes, and new business models. The food system needs to become far more circular, with side streams from the process and food industries turned into new products. This would allow food and feed production to grow while using fewer resources. Industrial symbiosis, in which companies in the same area share energy, water, heat, and biomass, is an important tool. Diets can also be expected to change considerably, with more plant-based food, insects, microalgae, farmed marine organisms, and lab-grown meat. In developing countries, making better use of residual streams from agriculture and fisheries can reduce waste and create new sources of income.

What should be done?

- Include food systems in NDCs and National Adaptation Plans, with measures for both emissions reductions and climate adaptation.
- Reduce food loss and waste along the entire value chain, and keep organic waste out of landfills. A well-developed, efficient cold chain is key to reducing waste.
- Enable circular solutions in which side streams from the food and process industries become new food and feed, including through industrial symbiosis.
- Support the development of new protein sources such as plant-based food, insects, microalgae, and farmed marine organisms.
- Step up work on technologies, processes, and business models that cut energy and resource use from production to consumption.
- Develop technology and knowledge suited to the Global South, where food security is most vulnerable to climate change.

Circular Material Flows and Waste Management

NTNU: Paritosh C. Deshpande, Corinna Schulze-Netzer
SINTEF: Anneli Alatalo Paulsen, Kristin Fjellheim

The construction sector is the world's largest consumer of materials, and material production accounts for a large share of global greenhouse gas emissions. Urbanisation, population growth, and major infrastructure investments, particularly in low- and middle-income countries, will sharply increase the volume of construction and demolition waste.

Plastics pose a separate challenge. Poor collection and waste management in construction, transport, textiles, fisheries, aquaculture, and agriculture pollute oceans and natural environments, and waste valuable material resources. Greater material circularity and better waste management are essential to prevent plastic pollution, reduce demand for virgin raw materials, and retain the value of plastic materials. This requires coordinated action along the whole value chain, from design and production to collection, reuse, and recycling.

The most effective way to cut material-related emissions is to avoid generating waste in the first place, rather than managing it afterwards. Smarter design, more efficient use of materials, and longer lifetimes reduce material consumption. Reuse and upcycling retain the value of materials, strengthen resource security, reduce emissions, and create markets for secondary materials.

Fractions that cannot be recycled, such as some plastic and hazardous waste and residual household waste, can replace coal and other fossil inputs in energy-intensive industries, particularly cement production. Co-processing of this kind cuts emissions and reduces reliance on landfills and open burning of waste, which is still widespread in many parts of the world.

Local and regional value chains for construction and demolition waste have considerable potential. They can combine waste management, resource utilisation, and industrial decarbonisation while creating local jobs and value.

What should be done?

- Establish a framework that encourages the recycling and reuse of construction and demolition waste.
- Prioritise preventing waste and reducing material use through resource-efficient design, longer service life, and smarter use of materials.
- Give priority to developing circular value chains for secondary building materials and other material resources.
- Adopt co-processing as part of strategies for both managing waste and cutting industrial emissions.
- Develop standards and quality requirements that build trust in products made from reused and recycled materials.
- Strengthen international cooperation on developing technology, sharing knowledge, and building capacity for a circular construction sector, particularly in fast-growing urban regions in low- and middle-income countries.

Minerals and Critical Raw Materials

NTNU: Gabriella Tranell, Kurt Aasly
SINTEF: Ana Maria Martinez, Lisbeth-Ingrid Alnæs

The green and digital transitions are driving up demand for many minerals, which will call for more extraction, recycling, and recovery. Many of the mineral resources needed are classified as critical raw materials (CRMs[16]): they are of high economic importance, essential to strategic value chains, and difficult to substitute with other minerals. CRMs can come from primary sources, meaning mining on land or on the seabed, and from secondary sources, meaning end-of-life products, by-products, or tailings from other industries. Supply also depends on the whole value chain, from extraction and processing to refining and manufacturing. Existing industry needs to be safeguarded, and new capacity built where needed. This matters most in regions such as Europe, which currently relies on imports at several stages of the value chain.

Demand for mineral resources is also rising in construction, where sand, gravel, crushed stone, and natural stone are essential raw materials. Whether for critical raw materials or construction, every stage from extraction and processing to refining, metal production, and recycling needs to cause as little harm as possible. Value chains should also become more efficient, for example through circular economy models, without harming nature or the environment or undermining social sustainability. No country or region can meet its entire demand for critical raw materials on its own. Resilient and sustainable value chains therefore depend on international cooperation and long-term partnerships between producer and consumer countries.

What should be done?

- Recover more critical raw materials from electronic waste, batteries, and buildings (urban mining), so that secondary sources meet a larger share of demand and valuable materials stay in use.
- Protect and strengthen existing production, and build complete value chains for critical raw materials through long-term international partnerships.
- Develop efficient technologies across the value chain that reduce the land and environmental footprint of extraction and processing.
- Make it possible to use residual materials from mines and industry rather than depositing them as waste.
- Support the development of technologies and products that use smaller amounts of critical raw materials, such as batteries that are cobalt-free and use less lithium.
- Require life cycle analyses, social life cycle analyses, and mapping of material flows along mineral value chains.
- Involve local communities and Indigenous peoples early when new mineral projects are planned, and make sure land-use planning takes their interests into account.
- Help producer countries, including those in the Global South, capture more value locally through international partnerships with high environmental standards.



Climate-Resilient Societies

Why this matters

Global warming is already changing how we build, plan, and manage our societies. Rising temperatures, more extreme weather, and shifting natural conditions pose new challenges for infrastructure, cities, buildings, and transport systems. This makes climate adaptation an increasingly important part of climate action.

The transition to a low-emission society also creates opportunities to develop solutions that are more energy-efficient, resilient, and sustainable. Buildings, energy systems, transport, and other critical infrastructure must be designed both to reduce emissions and to withstand a changing climate.

Building climate-resilient societies therefore takes more than adaptation alone. It means combining emissions reductions, civil protection and emergency preparedness, and quality of life in solutions that work in today's climate and in the climate to come.

Climate-Neutral, Energy-Efficient Buildings and Cities

NTNU: Arild Gustavsen
SINTEF: Judith Thomsen

Buildings, cities, and towns account for a large share of global energy use and greenhouse gas emissions. Meeting climate targets will require lower energy demand, more renewable energy, and smarter, more flexible solutions that integrate buildings, transport, and energy systems. The transition to climate-neutral, energy-efficient cities needs research, business, the public sector, and citizens to work together across the whole system. Research has shown that energy use in Norway's building stock could be halved by 2050.[17] This would free up 40 TWh of electricity to meet the growing demand for zero-emission electricity in transport and industry. Research also shows that the climate footprint of material use could be halved compared with current practice.[18] Achieving this means using materials more efficiently, renovating more, and extending the service life of existing buildings and materials.

Although climate-neutral and zero-emission solutions require up-front investment, evidence shows that they can still be profitable over their lifecycle.[19] This depends, among other things, on making fuller use of energy flexibility than we do today, through smart control and optimisation. Flagship projects can showcase innovative solutions, have a major impact on learning and skills development, help bring down costs, and drive innovation.[20] Climate-neutral, smart solutions for buildings, neighbourhoods, and cities can also create new jobs. Achieving rapid, fair, and cost-effective emissions reductions worldwide will require binding international cooperation on common standards and targets for climate-neutral buildings and cities.

What should be done?

- Reduce energy and electricity demand through energy efficiency, especially in the existing building stock.
- Prioritise renovating, converting, and extending the service life of existing buildings, and reusing materials and components.
- Use building-integrated solar systems (for electricity and heat), and heat pumps and district heating for heating. Heat pumps can also provide cooling, which will be increasingly needed as temperatures rise.
- Develop integrated urban strategies that combine energy, transport, buildings, and land use, in line with the EU Renewable Energy Directive[21] and the Electricity Market Directive.[22]
- Introduce clear price signals. Design tariffs that end users can easily respond to and that deliver the intended societal outcomes.
- Enable flexibility. Support coordinated solutions at building, district, and city level to use resources more efficiently.
- Strengthen collaboration. Step up joint efforts by business, academia, and the public sector to harness digitalisation and advance environmentally-sound district and urban development.
- Involve citizens. Ensure that the technologies deployed are inclusive, and engage citizens in ways that improve their quality of life.

Maritime Transport

NTNU: Sverre Steen
SINTEF: Trond Johnsen

The maritime sector accounts for about 3 % of global greenhouse gas emissions[23]. To reach zero emissions, the industry must improve energy efficiency, switch to new fuels, and build the infrastructure these fuels need. In 2023, the International Maritime Organization (IMO) adopted a strategy to cut emissions, relative to 2008, by 20 to 30 % in 2030 and 70 to 80 % in 2040, and to reach net zero around 2050[24]. A global regulatory framework to implement the strategy, the IMO Net-Zero Framework, was approved in 2025, but its adoption has been postponed[25]. The biggest challenge is therefore putting the strategy into practice.

Green fuels such as hydrogen, ammonia, methanol, and biofuels are still expensive, take up a lot of space on board, and are not available in large enough volumes. Producing them also requires large amounts of renewable power. Shipping is a highly cost-driven industry, and low- and zero-emission solutions still struggle to compete with fossil alternatives. Better logistics planning, route optimisation, modern hull design, and new propulsion systems can cut fuel consumption considerably, but day-to-day operations are often governed by cost alone, with no regard for emissions. On-board carbon capture and storage (CCS) is already available and, combined with biofuels, can deliver negative emissions. This depends on ports being able to receive the captured CO_2.

For international shipping, IMO regulations are the most important policy instrument. Cargo owners can help drive the transition by setting emissions requirements for the transport they buy, particularly in container shipping. Regional regulations have also proved effective, because shipowners and operators want their vessels to be able to sail in as many of the world's waters as possible. This allows regions such as the EU to shape developments worldwide. The transition will need integrated measures that combine efficiency, technology, and infrastructure, backed by cooperation along the entire value chain.

What should be done?

- Adopt and implement the IMO Net-Zero Framework.
- Introduce requirements for energy-saving technology and optimised ship designs, and provide support for them.
- Use contracts for difference to close the cost gap between green fuels and fossil alternatives.
- Increase investment in renewable power so that enough green fuel can be produced.
- Establish green shipping corridors with ports and infrastructure for zero-emission transport, including facilities to receive CO_2 captured on board.
- Use regional regulations to drive emissions reductions while global rules are put in place.

Sustainable Cooling

NTNU: Armin Hafner
SINTEF: Petter Nekså, Kristina Norne Widell

Cooling and heating are two sides of the same coin, and both are essential to modern society. Energy-efficient refrigeration systems, air conditioning, and heat pumps can deliver substantial gains across many sectors: heating and climate control in buildings, heating and cooling in industry, and not least the food cold chain, from farm to fridge. Integrated systems that meet both cooling and heating needs can also have a major impact. Supermarkets that use a single CO_2 system for refrigeration, freezing, and heating have cut their electricity consumption by around 35 %.

All these systems rely on refrigerants, gases that circulate within the system. Much of today's cooling technology uses gases that harm the climate or the environment, and some of it consumes a lot of energy. The Montreal Protocol, in force since 1989, phased out ozone-depleting CFCs, but many of their replacements, HFCs, have turned out to be very potent greenhouse gases. Switching to alternatives that are safe for both the ozone layer and the climate could on its own avoid up to 0.5 °C of global warming by the end of this century[26].

The newest generation of these gases, HFOs, has little climate impact, but HFOs belong to the PFAS group[27], and some break down into "forever chemicals" that accumulate in nature and are extremely difficult to remove. The answer is natural refrigerants: CO_2, ammonia, hydrocarbons, water, and air. They harm neither the ozone layer nor the climate, pose no long-term health risks, and can save energy.

Many countries in the Global South can leapfrog straight to natural refrigerants and avoid costly stopgap technologies that would soon need phasing out. According to UNEP, sustainable cooling could help more than a billion people adapt to climate change and save an estimated USD 17 trillion in energy transition costs by 2030[28]. Current standards are an obstacle, however, because they limit how much flammable refrigerant a system can contain.

What should be done?

- Require solutions based on natural refrigerants such as CO_2, ammonia, hydrocarbons, and water in public procurement.
- Introduce a phase-out of fluorinated refrigerants in line with the EU F-gas Regulation[29] and strengthen research into solutions based on natural refrigerants.
- Introduce incentives that ensure all fluorinated refrigerants are collected and destroyed, including PFAS-based refrigerants not covered by existing GWP-based return schemes.
- Update standards for flammable refrigerants to allow larger hydrocarbon charge sizes in refrigeration systems and heat pumps for buildings and industry.
- Support the development of high-temperature heat pumps that use natural working fluids to deliver process heat at 100–200 °C, replacing fossil heat sources in industry.



7

A Just Transition and Cooperation with the Global South

A Just Transition and Cooperation with the Global South

NTNU: Rolee Aranya, Pedro Crespo del Granado
SINTEF: Kristina Norne Widell, Petter Støa, Anneli Alatalo Paulsen, Shraddha Mehta

The green transition will not succeed if technology, expertise, and investment remain concentrated in high-income countries. Many of the countries expected to see the fastest growth in population, energy demand, and industrial development in the coming decades are also among the most vulnerable to climate change. A just transition therefore means cutting emissions while securing access to energy, jobs, food, healthcare, and economic development.



By technology, we mean more than products and stand-alone solutions. Technology shapes how societies are built and how they work in practice: how energy is produced and distributed, how food systems are organised, how industry develops, and how public services are delivered. Experience shows that technology only makes a lasting difference when it is part of wider systems for use, operation, and value creation. Technical solutions also need to be developed in step with the expertise, institutions, markets, and policy framework around them.

Targeted international technology collaboration is therefore not mainly about transferring ready-made solutions. Its aim should be to build local skills and expertise, strengthen institutions, and help societies and economies develop on their own terms. When research, industry, government, and civil society work together as equal partners, they can turn knowledge into action, build new value chains, and scale up solutions. In this way, technology can help cut emissions, create value locally, and support lasting development.

What needs to happen?

Equal Partnerships

Results are usually best when research, industry, government, and civil society tackle shared challenges together. Long-term partnerships make it possible to build skills and expertise, strengthen institutions, and develop solutions suited to the needs and policy framework of each country. The aim should be collaboration with results that outlast individual projects.

Collaborative Technology Development

Technology creates the most value when it is developed and deployed together with the people who will use it. Experience from international collaboration shows that handing over ready-made solutions does not, on its own, lead to lasting development. Technology has to be linked to skills development, institution-building, and local priorities. The aim is to strengthen partner countries' own ability to develop solutions further and shape their own development path.

Research and Higher Education as Drivers of Development

Research and higher education are essential for building expertise, developing institutions, and training the next generation of leaders and specialists. Universities and research institutions bring industry and government together with the research community, and help turn new knowledge into practical solutions. Investment in knowledge tends to have the most lasting impact on development.

Local Value Creation and Jobs

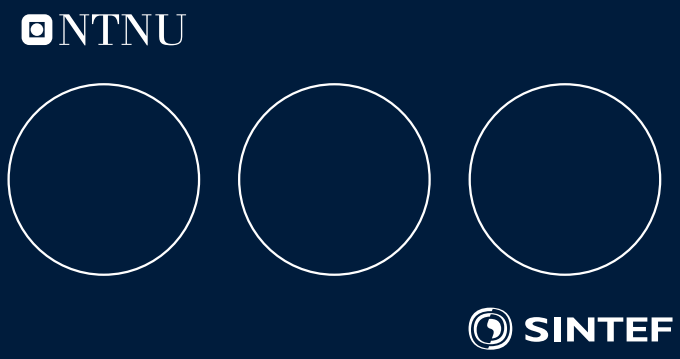
The green transition must deliver jobs, new businesses, and economic growth. When technologies are developed, adapted, and deployed locally, they lay the foundations for new value chains, greater value creation, and more economic room to manoeuvre. Choosing a technology is also a choice about jobs, skills, and the direction a society takes. Local value creation should therefore be a central aim of international technology collaboration.

Financing That Supports Development

Many good solutions never get off the ground because access to capital, expertise, and markets is limited. Public policy instruments, development finance, and partnerships with the private sector can reduce risk and help more projects go ahead. Experience shows that finance has the greatest effect when it is planned together with skills development and long-term partnerships.

Notes

1. Intergovernmental Panel on Climate Change. (2021). Summary for policymakers. In *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/
2. International Energy Agency. (2025). *Global methane tracker 2025*. https://www.iea.org/reports/global-methane-tracker-2025
3. GWP over a 100-year time horizon (GWP100). Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis*. Cambridge University Press.
4. DNV. (2023). *Energy transition outlook 2023*.
5. NOAA Global Monitoring Laboratory. (n.d.). *Trends in atmospheric sulfur hexafluoride*. https://gml.noaa.gov/ccgg/trends_sf6/
6. COP29 Presidency. (2024). *COP29 global energy storage and grids pledge*.
7. International Energy Agency. (2024). *World energy investment 2024*. https://www.iea.org/reports/world-energy-investment-2024
8. International Energy Agency. (2023). *Renewables 2023*. https://www.iea.org/reports/renewables-2023
9. European Environmental Bureau. (2024, July). *Land for renewables: Briefing on spatial requirements for a sustainable energy transition in Europe*. https://eeb.org/library/land-for-renewables-briefing-on-spatial-requirements-for-a-sustainable-energy-transition-in-europe/
10. World Wind Energy Association. (n.d.). *Global statistics*. https://wwindea.org/GlobalStatistics
11. International Energy Agency. (2019). *Offshore wind outlook 2019: World energy outlook special report*.
12. FME NorthWind. (2022, June 28). *Lighthouse initiatives on offshore wind explained i 3 minutes*. https://www.northwindresearch.no/news/lighthouse-initiatives-on-offshore-wind-explained-i-3-minutes/
13. International Energy Agency. (2023). *Net zero roadmap: A global pathway to keep the 1.5 °C goal in reach (2023 update)*.
14. Lebling, K., Schumer, C., & Riedl, D. (2023). *International governance of technological carbon removal: Surfacing questions, exploring solutions* (Working paper). World Resources Institute. https://doi.org/10.46830/wriwp.23.00013
15. Aina Benedikte Kristin Jordal, Odd Andersen, Ole Jacob Broch, Lilo Maria Keti Henke, Arne Karstein Røyset, Petra Rüther, Ragnhild Skagestad, Jorunn Skjermo, & Kathrin Yvonne Weber (2026). *Beyond emission cuts: Can we reverse the climate clock?* (Report No. 2026-00371). SINTEF Energi AS. https://hdl.handle.net/11250/5539568
16. European Commission. (n.d.). *Critical Raw Materials Act*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en
17. Sandberg, N. H., Dokka, T. H., Lien, A. B. G., Sartori, I., Skeie, K., Manrique Delgado, B., & Lassen, N. (2023). *Energispare-potensialet i bygg fram mot 2030 og 2050: Hva koster det å halvere energibruken i bygningsmassen?* [The energy-saving potential in buildings towards 2030 and 2050: What does it cost to halve energy use in the building stock?] (ZEN Report No. 50). SINTEF and NTNU.
18. Wiik, M. K., Fuglseth, M., Resch, E., Lausselet, C., Andresen, I., Brattebø, H., & Hahn, U. (2020). *Klimagasskrav til materialbruk i bygninger: Utvikling av grunnlag for å sette absolutte krav til klimagassutslipp fra materialbruk i norske bygninger* [Greenhouse gas requirements for material use in buildings: Developing a basis for absolute limits on emissions from material use in Norwegian buildings] (ZEN Report No. 24). SINTEF and NTNU.
19. Lien, A. B. G., Vågbø, P. C. B., Wigenstad, T., Jenssen, B., & Backe, S. (2024). *Merkostnader ved ZEN: En casestudie av Nidarvollutbyggingen i Trondheim* [Additional costs of ZEN: A case study of the Nidarvoll development in Trondheim] (ZEN Report No. 59). SINTEF and NTNU.
20. Almås, A.-J., Hauge, Å. L., & Klinski, M. (2015). *Markedseffekter av forbildeprogrammer* [Market effects of pilot-project programmes] (SINTEF Report SBF20150247). SINTEF.
21. European Commission. (n.d.). *Renewable Energy Directive*. Retrieved August 8, 2024, from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
22. European Commission. (n.d.). *Electricity market design*. Retrieved August 8, 2024, from https://energy.ec.europa.eu/topics/markets-and-consumers/electricity-market-design_en
23. International Maritime Organization. (2020). *Fourth IMO GHG study 2020*. https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx
24. International Maritime Organization. (2023). *2023 IMO strategy on reduction of GHG emissions from ships*. https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx
25. International Maritime Organization. (2025, October). *IMO's Marine Environment Protection Committee adjourns discussions on the adoption of the Net-Zero Framework for one year* [Press briefing]. https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-net-zero-shipping-talks-to-resume-in-2026.aspx
26. U.S. Environmental Protection Agency. (n.d.). *Frequent questions on the phasedown of hydrofluorocarbons*. https://www.epa.gov/climate-hfcs-reduction/frequent-questions-phasedown-hydrofluorocarbons
27. European Chemicals Agency. (n.d.). *Per- and polyfluoroalkyl substances (PFAS)*. https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas
28. United Nations Environment Programme. (2023). *Global cooling watch 2023: Keeping it chill: How to meet cooling demands while cutting emissions*. https://www.unep.org/resources/global-cooling-watch-2023
29. European Commission. (n.d.). *EU rules on fluorinated greenhouse gases*. https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-rules_en


NTNU
SINTEF