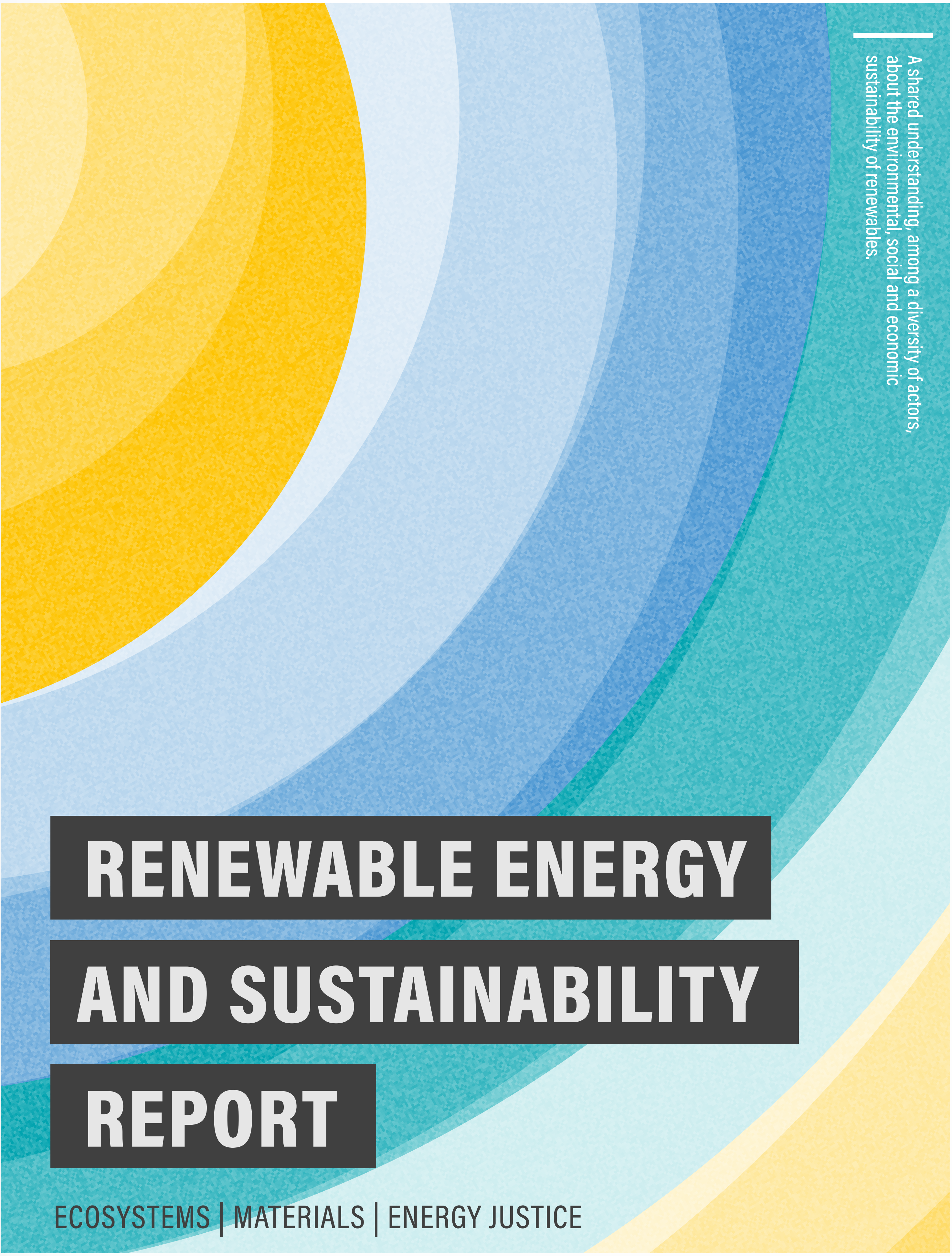
REN21
RENEWABLES NOW



A shared understanding, among a diversity of actors, about the environmental, social and economic sustainability of renewables.

RENEWABLE ENERGY AND SUSTAINABILITY REPORT

ECOSYSTEMS | MATERIALS | ENERGY JUSTICE

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FOREWORD

The shift away from fossil fuels is imperative for the health of our communities and the environment. It is also widely acknowledged that we need to move to an efficient, renewable-based energy system. In today's energy landscape, a recurring question on many people's mind is: *How sustainable are renewables*?

This question sparks considerable debate, drawing scrutiny from various angles. It is often fuelled by misinformation, and can generate a form of resistance to the deployment of renewables. While it is essential to acknowledge that, like any infrastructure, the deployment of renewables may have associated environmental and social impacts, in the present triple planetary crisis of climate change, pollution and biodiversity loss, it is imperative to assess these impacts carefully, while acknowledging the broader benefits of renewables. It is also important to assess these impacts in comparison with the impacts of other energy sources.

REN21's *Renewable Energy and Sustainability Report* (RESR) is designed as a reference document that analyses the benefits and potential negative impacts of renewable energy deployment. It takes stock of the wealth of existing solutions and best practices across the world to maximise the benefits of renewables while minimising their potential negative impacts. Establishing these benchmarks is central for paving the way towards a sustainable transition to renewables while also building the necessary trust and societal support.

Given the complexity and sensitivity of the topic, debate – sometimes heated – was at the heart of RESR production. The creation of a safe space for multi-stakeholder and multi-sectoral consultation and dialogue was central to the report production process. Bringing these different perspectives and "languages" together was no small task, but it was essential for developing a reference report within and beyond the energy sector and for building a shared understanding of sustainable practice and implementation pathways. We used an extensive collaborative process – building on decentralised crowd-sourced data, knowledge and insights – to develop the largest body of data and knowledge on the topic.

After a year of research, extensive data collection, exchanges, authoring and several rounds of review, the RESR stands as a testament to the engagement of many, diverse players. I would like to thank all of them – authors, special advisors, contributors and reviewers – for sharing their knowledge and insights and engaging in this process. I would also like to thank the project team at the REN21 Secretariat, and in particular Andrea Wainer as the project manager, for their continuous dedication to the topic, the report and the community. This has been a fantastic, collaborative journey to make the RESR a reality.

As a reader, I hope you will find in this report some of the answers and solutions you need in your work in the energy transition, climate change, environmental protection, sustainable development, and labour and human rights. It is clear that the process does not end here. We need to collectively spread the insights of the RESR and use them in dialogue and debates to advance the shift to renewables. The evolution of sustainability knowledge, practice and policies is a dynamic process. The continuous tracking of these trends will be important.

To me, this RESR is a clear call to action, to move from the fossil fuel era to the renewable energy era in the most accelerated and most sustainable way.

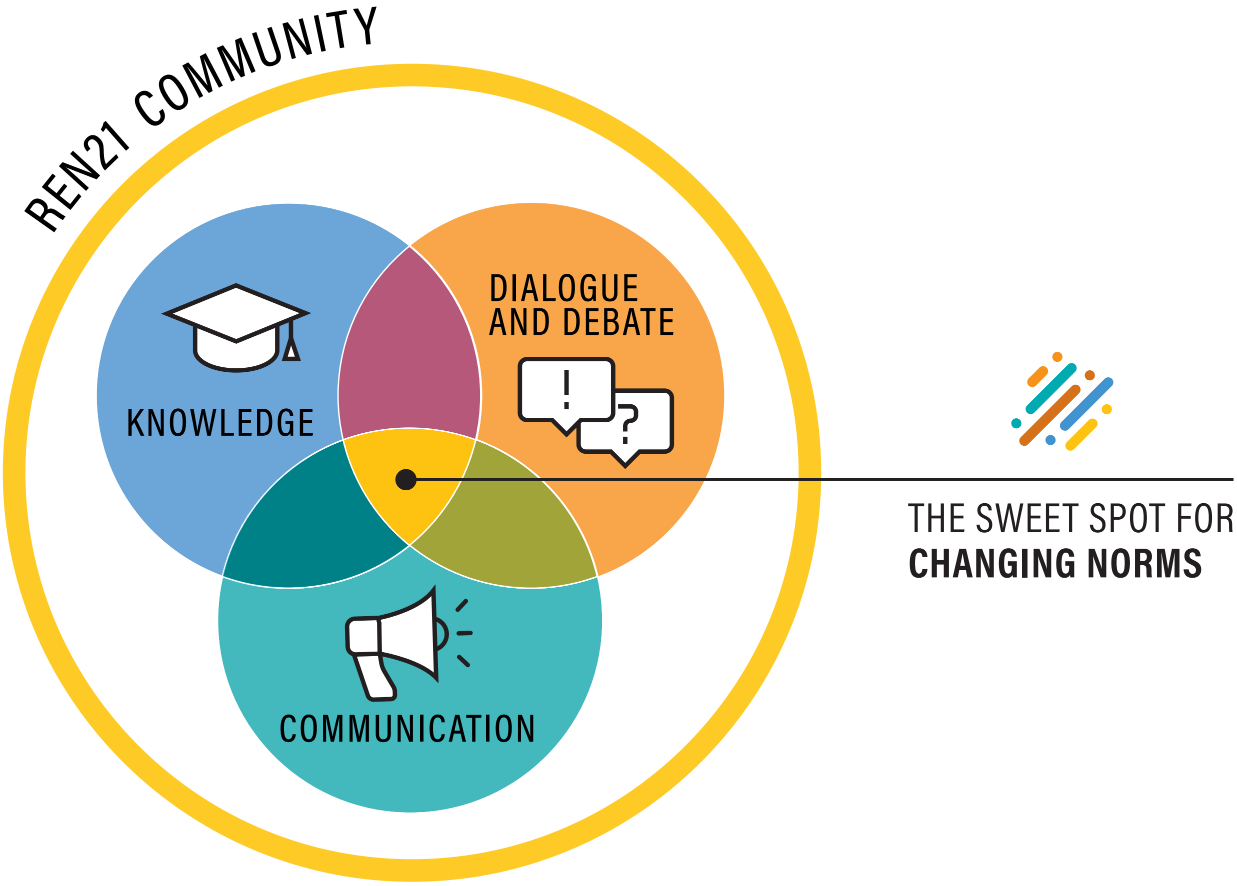
Rana Adib
Executive Director

REN21
RENEWABLES NOW

REN21 is the only global renewable energy community that brings together actors from science, academia, governments, NGOs and industry to collectively drive the rapid, fair transition to renewables.

Founded in 2004, REN21 has 20 years of experience in providing credible insights and connecting ecosystems inside and outside the renewable energy sphere. Our objective is to support and accelerate the transition to renewable energy.

Today, REN21 drives the renewable energy transition by creating an enabling environment for renewables to become the obvious choice. We ensure a systemic approach, opening multi-sectoral and inter-disciplinary spaces for communication and debate to drive the uptake of renewables. Our ever-growing community comprises over 100 members and more than 4,000 experts from all regions who continuously contribute to REN21's knowledge, dialogue and communication efforts. Collectively, we work to drive the rapid uptake of renewables. Together. NOW.



REN21
CROWD-SOURCED DATA
AND KNOWLEDGE

REN21 reports carrying the *REN21 Crowd-Sourced Data and Knowledge* stamp verify that the following collaborative process was applied:

- Developing data collection methods that build on a global multi-stakeholder community of experts from diverse sectors, enabling access to dispersed data and information that frequently are not consolidated and are difficult to collect.
- Consolidating formal (official) and informal (unofficial/unconventional) data gathered from a wide range of sources in a collaborative and transparent way, for example, by using extensive referencing.
- Complementing and validating data and information in an open peer-review process.
- Obtaining expert input on renewable energy trends through interviews and personal communication between the REN21 team and authors.
- Using validated data and information to provide fact-based evidence and to develop a supportive narrative to shape the sectoral, regional or global debate on the energy transition, monitor advancements and inform decision processes.
- Making data and information openly available and clearly documenting our sources so they can be used by people in their work to advocate for renewable energy.
- Using crowd-sourced data to develop a shared language and create an understanding as the foundation for collaboration.

DISCLAIMER

REN21 releases issue papers and reports to emphasise the importance of renewable energy and to generate discussion on issues central to the promotion of renewable energy. While REN21 papers and reports have benefited from the considerations and input from the REN21 community, they do not necessarily represent a consensus among network participants on any given point. Although the information given in this report is the best available to the authors at the time, REN21 and its participants cannot be held liable for its accuracy and correctness. The designations employed and the presentation of material in the maps in this report do not imply the expression of any opinion whatsoever concerning the legal status of any region, country, territory, city or area or of its authorities, and is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers or boundaries and to the name of any territory, city or area.

This report was commissioned by REN21 and produced in collaboration with a global network of research partners. A large share of the research for this report was conducted on a voluntary basis.

Report Citation:

REN21. 2023. Renewable Energy and Sustainability Report
(Paris: REN21 Secretariat).

ISBN: 978-3-948393-12-0

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Funded by

Federal Ministry
Republic of Austria
Climate Action, Environment,
Energy, Mobility,
Innovation and Technology

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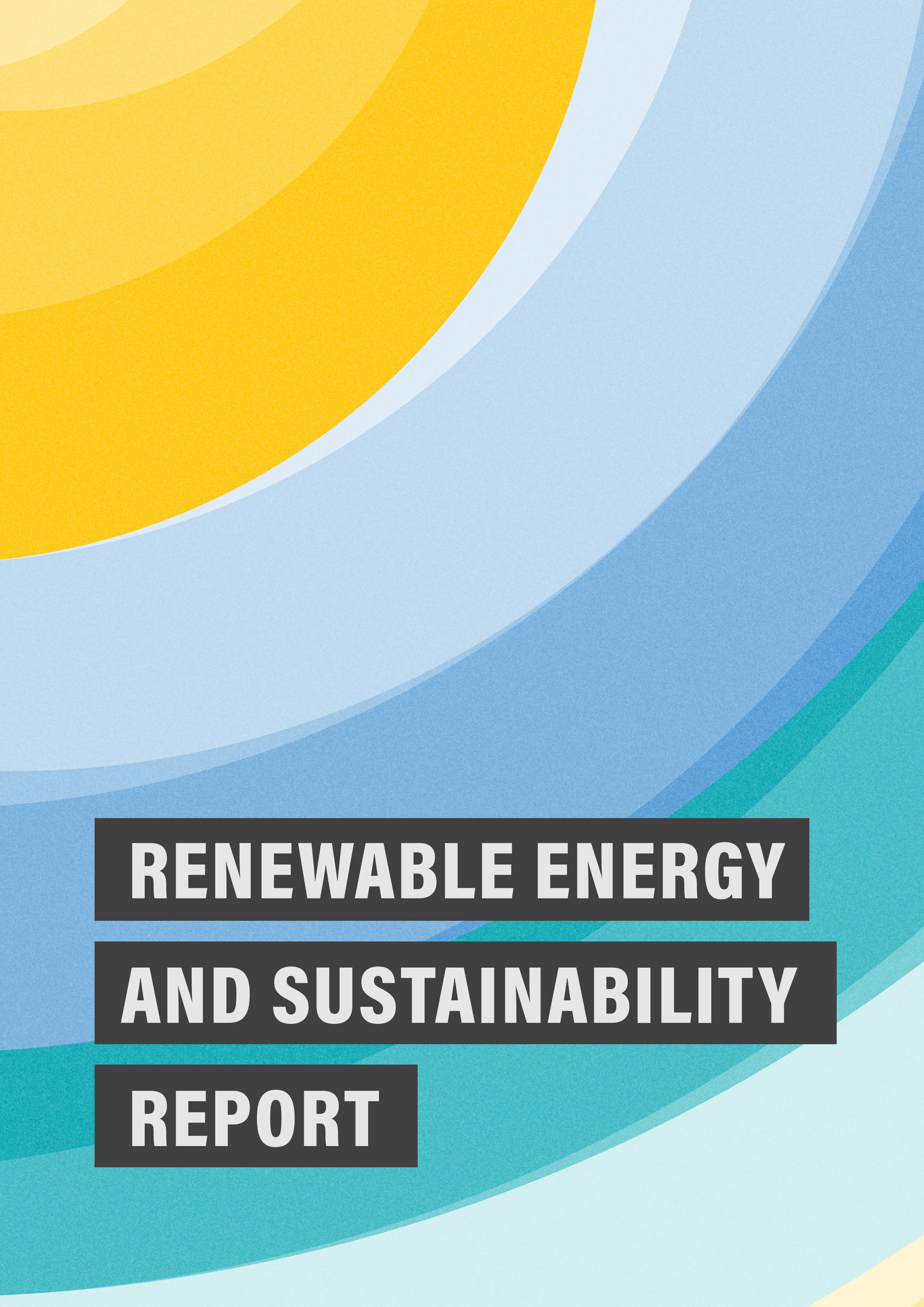

RENEWABLE ENERGY AND SUSTAINABILITY REPORT

TAKEAWAYS AND PERSPECTIVES

The exploration, production, consumption and combustion of fossil fuels are the main drivers of climate change. Phasing out fossil fuels is necessary to address climate change, and transitioning towards an efficient energy system based on renewable energy sources is widely recognised as the key solution to tackle the triple planetary crisis of climate change, pollution and biodiversity loss.

The transition to a renewables-based energy system is a unique opportunity to build a more inclusive and fairer energy system, economy and society. In addition to drastically reducing greenhouse gas emissions and pollution – thereby mitigating climate change and improving human health – renewable energy can enable local energy production. This can support energy security and offers the potential to reduce conflicts over resources. Renewables can foster energy access, support local industrial and economic development, create jobs, and enable bottom-up, decentralised governance and energy democracy.

Next to these benefits, the deployment of renewable energy - as with any infrastructure - can have negative impacts on the environment and human well-being if measures are not taken to avoid these effects. It is therefore crucial to gain a complete understanding of potential negative impacts in order to develop strategies for avoiding or mitigating them, while maximising the benefits of renewable energy.

Widespread disinformation continues to fuel scepticism about the reliability of a renewables-based energy system, including the ability of the industry to deploy the needed capacities and to secure the required materials. Despite strong evidence of the transformative potential of renewables and their clear benefits over fossil fuels, the overall environmental, social and economic sustainability of these technologies is still being called into question.

These concerns have fuelled opposition from diverse actors and sectors, which has introduced misunderstandings about the possibilities offered by renewables and the pressing need for the energy transition. In the face of the climate emergency, it is critical to respond to these concerns, promote evidence-based policy making, and reinforce societal support for the deployment of renewables and their necessary infrastructure.

The *Renewable Energy and Sustainability Report* (RESR) presents existing knowledge about the environmental, social and economic sustainability of renewables. It strives to identify positive impacts as well as challenges – mapping out the arguments circulating in the public space and seeking to differentiate facts from myths – with the goal of highlighting workable solutions to the identified challenges.

The following are some key takeaways from the research as well as the report production process.

SUPPORTING BETTER DECISIONS WITH BETTER DATA

Reliable and credible data are key to inform decision makers. However, assessing the environmental and social sustainability of renewables is complex. It requires a holistic approach and comprehensive data from diverse sources. A rapidly expanding body of research is currently investigating the sustainability of renewables. This literature demonstrates the clear environmental and social advantages of renewable energy over fossil fuels, and the possibility of mitigating or eliminating their potential negative impacts.

Nonetheless, in-depth studies and consolidated data on renewables and sustainability are still lacking in many important areas, such as land use, water use and materials requirements. The nature and scale of the resource demands and environmental impacts associated with energy provision and infrastructure vary depending on a range of factors, including the technology in question, the deployment method and the location. Generic statements overlook these specificities and oversimplify complex realities. Global data need to be complemented by regional, national and local data. Sectoral and technology-specific data are required to enable systemic assessments.

As the energy transition advances, novel solutions are emerging at a rapid pace. This requires continuous tracking of data, policies and trends on the sustainability of renewables, as it is important to close data gaps and to provide consolidated and timely information.

It is essential to build the evidence using a crowd-sourced, multi-stakeholder-based-approach that reflects diverse perspectives. This approach is crucial for establishing trusted evidence and a common ground for the energy transition.


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SUSTAINABILITY: THE COMPLEXITY OF DIVERSE PERSPECTIVES

Sustainability is a complex topic requiring continuous attention in policy and regulation. To build a shared understanding of the environmental, economic and social implications of shifting towards a renewables-based energy system, it is critical to involve a diversity of stakeholders through open consultation and participatory governance. This can help to bridge divergent and sometimes controversial perspectives. Participatory processes are essential to identify, promote, implement and support best practices from regulators and industry.

MAINSTREAMING BEST PRACTICES: AVOIDING, REDUCING AND MITIGATING RISKS

The RESR highlights many good practices, effective regulations, industry standards and inspiring initiatives to maximise the benefits and advance the sustainability of renewables. Several of the principles and best practices that should be applied to ensure the sustainable deployment of renewable energy infrastructure are summarised below.

To avoid or minimise potential negative impacts on land, water, and biodiversity, **careful siting** of renewable energy infrastructure can be conducted through **sensitivity mapping** and **environmental assessments** to avoid endangering critical habitats and species and disrupting local communities.

Regulations, community engagement and industry standards can promote:

- the deployment of renewables on **degraded land or former industrial, contaminated and marginal lands**; the integration of renewables in **existing infrastructure** such as rooftops, railway infrastructure, highways and floating platforms; and the **use of waste streams** in energy production;
- **multiple uses of land and water**, such as integrated solar photovoltaics (PV), agrivoltaics, floating solar PV, aquaculture with offshore wind farms, agriculture and grazing with onshore wind farms, **and nature-positive management** of land used for for renewable energy installations as well as for grid infrastructure;
- **sustainable agricultural practices**, such as agroforestry, sustainable crop rotations, appropriate feedstock selection and natural pest control. In the case

of bioenergy, owing to the diversity of technologies, feedstocks and locations, the assessment of their positive and negative impacts is extremely complex, and triggers opposing views. Moreover, global and reliable data on the actual shares of different feedstocks used are scarce and sometimes contradictory. This highlights the need to access reliable and granular data at the global scale, alongside the need to harmonise sustainability standards, regulations and enforcing mechanisms across supply chains.

- standards to **combat unsustainable practices** such as illegal logging, deforestation and pollution;
- **the involvement of all relevant stakeholders** in planning processes, and especially those potentially affected by the deployment of new infrastructure, to ensure that diverse perspectives are integrated and that local knowledge is used to maximise benefits;
- **the protection of human rights** – including land rights, labour rights, and the rights of Indigenous Peoples (such as through the implementation of Free, Prior and Informed Consent, FPIC) – as well as the inclusion of women along the renewable energy supply chain;
- **third-party verification and mandatory due diligence** to ensure that regulations are implemented effectively.

Targeted policies can also contribute to the development of local economies, create jobs, foster inclusivity and reduce inequalities. For example:

- Regulations can **require shares of local components** for new renewable energy projects (industry and services); set up **skilling and re-skilling programmes** including targeting workers shifting from the fossil fuel industry, women and minorities; and mandate **shares of local ownership** of energy projects, **community ownership** or **(co)-equity models**.
- National and local policies can **mandate or incentivise citizen participation** and **support community-led energy projects**.
- For **energy access** and the **deployment of renewables in low-income countries**, governments and development finance institutions play a key role in setting a supportive policy framework. Tools to enable financial flows to such deployments include sustainable finance, climate finance, grant financing, concessional loans, and dedicated funds – through the use of taxonomies and ESG (environmental, social and governance) requirements from financial institutions – and Just Energy Transition Partnerships.
- **Adjusting international trade treaties** can foster domestic renewable energy industries. This is especially important in developing countries to enable a just transition to a renewables-based economy.

To reduce resource demands, **the principles of the circular economy and energy efficiency can be applied**: redesign, reduce, repair and renovate, re-use, recover and recycle.

- While all forms of energy generation have an environmental impact, **energy and material efficiency** have a central role in reducing overall energy demand. This reduces the amount of energy that needs to be supplied and the infrastructure that needs to be built.
- **Design choices** in the deployment of renewable energy systems can minimise the use of non-renewable materials (such as critical minerals) and ensure easy **repair, re-use and recycling**.
- To enhance circularity in renewable energy, policies should provide **economic incentives for recycling and repurposing**, alongside implementing safety standards for repurposed components, technician training and bans on electronic waste landfilling. These measures include public subsidies, certification standards and mandatory collection of end-of-life components. Policies should also promote **research and development** for sustainable design.

THE WAY FORWARD

The RESR is a first step in the process of building the common vision required to accelerate the sustainable deployment of renewable energy. The report aims to inform decision makers and to serve as the basis for continuous dialogue and debate across a variety of stakeholders.

The report should be seen as the starting point of a dynamic process of continuous tracking and dissemination of evolving best practices and trends. These include evolving and emerging policies, regulations and standards, technological advancements, inspiring initiatives as well as emerging concerns. Complementing data with dialogues is essential to grow and improve the knowledge base, spread the findings of the report and amplify key messages. Data gaps and emerging topics identified in the RESR can be the basis for further research and knowledge-sharing activities.

Advancing a common understanding around the sustainability of renewables is key to maximising the benefits of the energy transition, and ultimately to accelerating the urgently needed shift to a renewables-based energy system, economy and society.

RECOMMENDATIONS:

Embrace complexity, and communicate about it

Renewables are the most sustainable energy source, without a doubt. In the context of ever-increasing disinformation fuelling opposition against renewables, it is of major importance **to accurately inform the public about the complexities of the data under scrutiny, how these data are analysed, and the diverse ways in which the best outcomes can be achieved**. Complex messages are difficult to convey and to simplify. Oversimplifying the issues at play or omitting those that could unveil fragilities or tension points do not allow for an effective understanding of what needs to be done to sustainably deploy renewables, and, especially, **how**. Moreover, such an approach can result in distrust and opposition. While more disaggregated and updated data are essential to better understand all benefits and potential impacts of renewables deployment, **communication efforts should raise awareness about the importance of the context and details when assessing sustainability.**

Take responsibility (and action)

- **Decision makers and authorities at the supra-national, national and local levels have the duty to define the norms for sustainable practices**. They can set the rules that need to be followed to implement such practices, as well as put in place appropriate enforcing mechanisms.

- **Public and private financial institutions should** back these rules and requirements and help channel funds where they are most needed, in ways that do not compromise the economies of vulnerable countries.

- **Industry players should fully embrace sustainability and actively avoid or mitigate possible negative impacts of renewable energy deployment** while considering the perspectives and potential losses of possibly affected communities and the health of ecosystems. Not only is it ethically right, but companies also have a commercial interest in preventing projects from being delayed, blocked and abandoned, which ultimately leads to economic losses and might fuel distrust in renewables. **Global sustainability standards based on multi-stakeholder governance** – such as the pioneering Hydropower Sustainability Standard – help renewable energy projects build trust among diverse stakeholder groups, and provide a fair and transparent platform for good faith discussions on complex energy challenges.

- It is also important to look at **unsustainable, illegal practices**, which exist across all sectors of the current economic system. The scope of this report was not to systematically track and report them, but rather to identify good practices and implementation pathways. Here too, it is the role of authorities to set rules, track compliance, and enforce regulations, whereas civil society organisations can contribute with awareness raising and advocacy. Companies benefit from identifying risks and putting safeguards in place. A multi-stakeholder approach for standards and certifications is key to prevent abuses, and several effective examples are highlighted in the RESR.


Gaganjit Singh / UN Women


Jessica Reeder / BlackRockSolar

- **Citizens and communities can contribute essential input to energy planning and should engage and be empowered to do so.** A just and sustainable energy transition also relies on the ability of citizens and communities to propose and implement solutions, from advocating and participating in decision making, to taking active ownership of energy assets.

The question is no longer about the obvious necessity of immediately deploying renewables. Rather it is about how to scale them rapidly and in ways that unlock their benefits and minimise potential negative impacts.

Market actors, governments and citizens all have a role to play in fulfiling this objective. The RESR documents the transformative potential of renewables and offers an initial shared understanding about their sustainability.

01

INTRODUCTION

01

INTRODUCTION

WHY RENEWABLES AND SUSTAINABILITY

The world faces an unprecedented "triple planetary crisis", interlinking climate change, biodiversity loss and pollution.[1] The global energy sector – which relies heavily on the exploration, extraction and combustion of fossil fuels (oil, gas and coal) – is responsible for the largest share of human-induced greenhouse gas emissions and is among the main causes of global warming.[2] Phasing out fossil fuels is necessary for addressing climate change, and transitioning to an efficient energy system based on renewable energy sources is widely recognised as a key solution.[3] Such a transition is critical and urgent if the world is to achieve the goal of keeping the average global temperature rise below 1.5 degrees Celsius (°C), as set out in the 2015 Paris Agreement.[4]

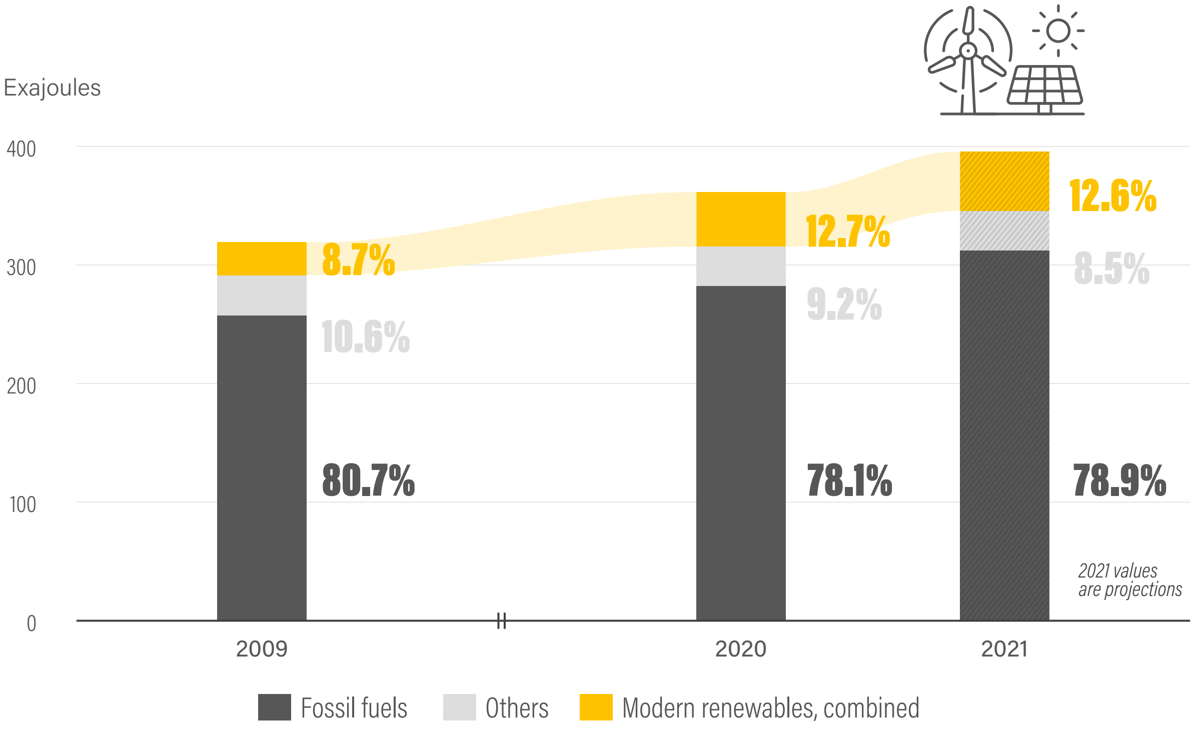
Renewables can provide much more than low-carbon energy. The energy transition represents a unique opportunity to build a more inclusive and fairer energy economy and society. By mitigating global warming and pollution, the transition to renewable energy can help reduce biodiversity loss. In addition, renewables can support energy security, as their decentralised nature enables local energy production and resilient energy supply. Potentially, they reduce conflicts linked to energy. Renewables are key to accelerating energy access in remote areas and can improve resilience during emergency situations, such as extreme weather events or wars.[5]

The uptake of renewable energy can be a driver for local industrial and economic development, including by creating jobs. In addition, renewables enable bottom-up, decentralised governance and energy democracy, allowing for new (co-)equity models.[6]

However, next to the benefits, the deployment of renewable energy – as with any infrastructure – can have negative impacts on the environment and human well-being if measures are not taken to avoid such impacts. It is therefore crucial to gain a complete understanding of these impacts in order to develop strategies for avoiding or mitigating them, while maximising the benefits of renewable energy.

Globally, the energy transition is not happening quickly enough. As of 2021, modern renewables accounted for only 12.6% of the global energy supply (► **see Figure 1**).[7] The world is far from being on track to reach the targets of the Paris Agreement, and it continues to lag on efforts to achieve the United Nations Sustainable Development Goals (SDGs) by 2030, especially SDG 7 on "access to affordable, reliable, sustainable and modern energy for all".[8] This is largely because unprecedented financial resources continue to be mobilised to support investment and subsidies for fossil fuels, and investment in renewable energy is insufficient.[9] Shifting the energy system away from fossil fuels to renewable energy will require increasing and accelerating the deployment of renewable energy capacity as well as enabling infrastructure (► **see Sidebar 1, p. 27**).

FIGURE 1. Share of Modern Renewable Energy in Total Final Energy Consumption, 2009, 2020 and 2021



Source: *See endnote 7 for this chapter.*

Disinformation about renewable energy remains widespread, leading sceptics to question the reliability of a renewables-based energy system, the ability of the industry to deploy the capacities needed, the availability of the materials required, and the overall environmental, social and economic sustainability of these technologies. Such concerns have fuelled opposition from diverse players and contribute to confusion and misunderstandings about the possibilities offered by renewables and the need for the energy transition.[10] Given the rising climate emergency, reinforcing and ensuring continuous societal support for the deployment of renewables and the necessary infrastructure is more urgent than ever.

PURPOSE OF THIS REPORT

The *Renewable Energy and Sustainability Report* (RESR) aims to build a shared understanding, among a diversity of actors, about the environmental, social and economic sustainability of renewables. Building on REN21's unique, collaborative approach, the report brings together diverse perspectives on the current debate, with the objective of building common ground and a shared pathway forward. It strives to identify positive impacts as well as challenges – mapping out the arguments circulating in the public space and seeking to differentiate facts from myths – in order to shed light on workable solutions to the identified challenges.

The RESR builds on an accumulated wealth of knowledge that goes beyond the energy sphere, with the aim of breaking silos and bridging viewpoints across environmental, labour, human rights and financial organisations; industry actors; and academia, among others. Solutions towards improving the sustainability of renewables do exist, and guidelines and standards are plentiful. The RESR attempts to provide an overview of existing best practices in policy, industry, civil society and beyond.

THE FOUNDATIONS OF SUSTAINABILITY

Developing a shared understanding of the sustainability of renewables calls for a closer look at how sustainability has been considered historically and how environmental policy has been discussed in the institutional arena in recent decades.[11]

For millennia, local communities and Indigenous Peoples have relied on traditional knowledge when interacting with the natural environment.[12] This knowledge recognises the relationships and interdependences of humans with natural events, land, water, fauna and flora in specific places and communities; as such, it sets the foundations for sustainable practices in all human activities.[13]

However, "sustainability" as a formal concept entered the international agenda only in the second half of the 20th century, amid growing concerns about the impacts of rapid industrial development.[14] In the 1960s and 1970s, landmark publications such as Rachel Carson's *Silent Spring* and the Club of Rome's *The Limits to Growth* brought attention to the existential risks that people and the planet face.[15] These works highlight the challenges resulting from rapid human population growth and an economic system that depends on the ever-increasing extraction (and waste) of finite resources, the introduction of toxic synthetic substances, and the degradation of natural ecosystems – all of which threaten humanity's survival.

The first United Nations Conference on the Human Environment, held in Stockholm, Sweden in 1972, formally recognised the "human right to nature".[16] Since then, in light of growing scientific knowledge about the impacts of human activities on the environment, the definitions of "sustainability" and "sustainable development", and various pathways for achieving these, have been key elements of international governance deliberations (► see Box 1).[17]

Despite these efforts, the concepts of sustainability and sustainable development continue to face criticism for being vague and at times controversial – for example, raising questions around what is meant by "development" and how it is measured. Similarly, the generally accepted three pillars of sustainability – environmental, social and economic – could be perceived as a framework of trade-offs that tends to favour "economic sustainability" (understood as economic growth) over the other critical dimensions.[18]

Box 1. Key Steps in the International Framing of Sustainability and Sustainable Development, Post-Stockholm

- In 1983, the United Nations General Assembly passed **Resolution 37/7**, recognising the relationship between human rights and the environment and calling on countries to protect the environment and promote sustainable development.
- In 1987, the **Brundtland Report ("Our Common Future")** defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The report highlighted the critical role that renewable energy must play if the world is to lessen its dependence on finite resources such as fossil fuels.
- In 1992, the **Earth Summit in Rio de Janeiro, Brazil** concluded that the concept of sustainable development was an attainable goal for all of the world's people and launched the action programme **"Agenda 21".**
- In 2000, the United Nations agreed on a set of eight **Millennium Development Goals (MDGs)** aimed at reducing extreme poverty, hunger and disease; improving access to clean water and sanitation; and promoting gender equality, education and environmental sustainability. However, critics highlighted the failure of the goals to integrate a more comprehensive approach to sustainability.
- In 2015, the MDGs were succeeded by the **Sustainable Development Goals (SDGs)**, a set of 17 goals that address not only poverty reduction but also economic growth, social inclusion, and environmental protection, including access to sustainable, reliable and affordable energy.
- In 2022, the UN General Assembly formally recognised the "**right to a clean, healthy and sustainable environment"** as a universal human right.

Source: *See endnote 17 for this chapter.*


Nabin Baral / IWMI

In the early 2000s, scientists identified a set of nine climatic thresholds, or "planetary boundaries", that, if crossed, would have severe consequences for all life on Earth.[19] Scientists updated this framework in 2023, warning that six of nine boundaries have now been crossed and one (ocean acidification) is approaching the threshold.[20] They found that only two of the boundaries – atmospheric aerosols and ozone depletion – remain within the limits of safe operation, underscoring the urgency of climate action.[21]

The concept of planetary boundaries laid the foundation for further frameworks describing the impacts of human activities on Earth's natural systems. For example, the "doughnut" economic model defines the social and ecological boundaries within which humanity must operate to meet the needs of all people while staying within Earth's ecological limits (► see Figure 2).[22] The inner ring of the model represents the minimum standards of well-being that must be met, while the outer ring shows the maximum levels of ecological impact that the planet can sustain. The "safe and just space for humanity" lies between the social and ecological boundaries.[23]

There is also growing global recognition of the limitations of the current economic system and its inadequacies in tackling the root causes of environmental degradation, poverty and inequality.[24] Diverse stakeholders have spoken of the urgent need to reduce material and resource use, shift towards more sustainable lifestyles and consumption patterns, and accelerate policy and behavioural changes at all levels of society – while pursuing broad co-operation across sectors and disciplines.[25]

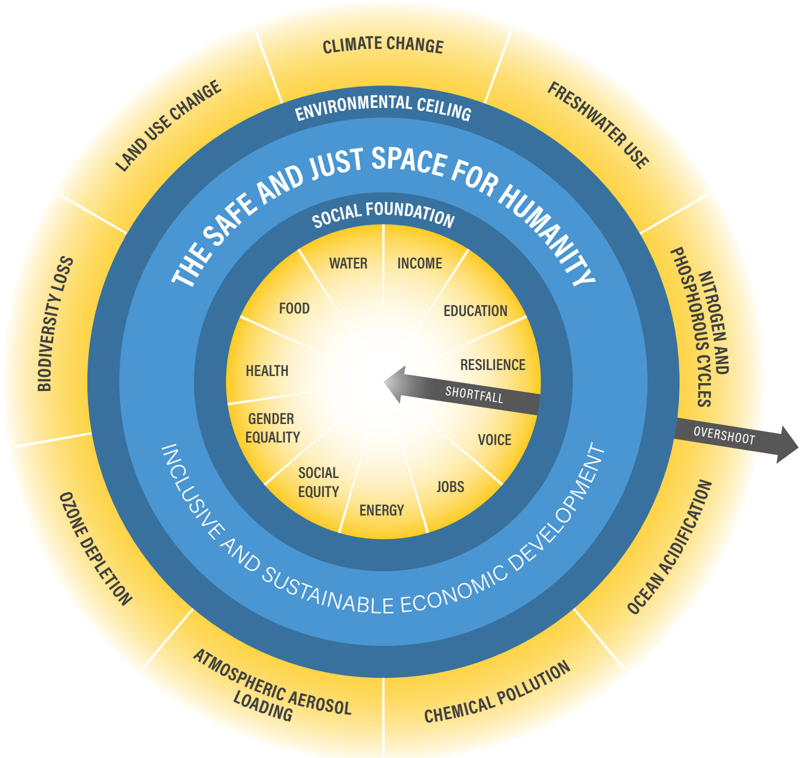
Many experts and organisations argue that it is necessary to move beyond business-as-usual approaches and to embrace radical system change that supports more sustainable, resilient and equitable societies, for the benefit of people and the planet.[26] (► See Special Focus 1 on sufficiency, p. 28.)

Measuring Sustainability

Measuring sustainability is a complex task, as it involves assessing the impact of human activities on the environment, society, and the economy, as well as considering the trade-offs among these different dimensions. Organisations worldwide have developed sustainability frameworks, indicators and assessment tools that apply to specific activities, objectives and scopes, which frequently use life cycle assessments to quantify the environmental impacts.[27]

Life cycle assessment, or LCA, is used to quantify the environmental impacts of a product, technology or service along the different stages of its life cycle, from the extraction of natural resources, to production, packaging, and distribution, to use and eventual waste management (e.g., landfill or recycling).[28] It attempts to quantify the direct or indirect environmental implications – such as pollutant emissions, water use and the consumption of valuable resources – of numerous interacting systems involved in an industrial process.[29] Although LCA has limitations (► see Box 2), the results can provide valuable information to help decision makers advance sustainability, for example through product selection or the adoption of specific standards or policies.[30]

FIGURE 2. Doughnut Economic Model



Source: *K. Raworth. See endnote 22 for this chapter.*

While such approaches are crucial for addressing specific challenges such as climate change, pollution, and materials use, it is increasingly understood that what is needed is a more holistic framework. Such a framework would consider the many economic, social and environmental dimensions of sustainability, and how they are inter-related, and ensure that stakeholders from diverse sectors – such as governments, business and civil society – are integrated into decision making.[31]

Implementing Sustainability

Assessment tools can inform sound decision making when choosing pathways for human activities. However, such decisions need to be guided by a common understanding of what the norms should be – in other words, ***what is acceptable*** for how different activities, such as energy production, are carried out.[32] Policies and regulations, together with proper monitoring and enforcement of compliance, are essential for setting such rules and advancing their implementation.[33]

At the global level, international treaties contribute to such norm- and rule-setting, providing a basis for shared values and objectives in diverse fields such as human rights, protection of the environment (including biodiversity), and labour and trade practices.[34] The legally binding Paris Agreement of 2015, and the outcomes of the yearly Conferences of the Parties to the

Box 2. Complexity of Life Cycle Assessment

Life cycle assessment can be a valuable tool and is widely used to establish goals to minimise negative impacts on the environment, and it can be conducted under international standards set by the International Organization for Standardization (ISO). The results of an LCA depend on how it is used, including methodological choices. For example, the decision of what processes are included, and where to start and end the study in the product's life cycle, influences the outcome. Often, data used to conduct an LCA also vary in availability, consistency and quality.

The level of granularity and detail of LCA differs across studies, with results varying greatly depending on the extent to which the full value chain of components is assessed, what types of emissions and pollutants are considered, and the time period over which impacts are measured. Assumptions about products, such as expected lifetime, also can make a significant difference. For example, if an LCA aims to calculate emissions per unit of potential energy output, results vary widely if assuming a lifetime of 20 years versus 40 years.

Systematic review and harmonisation can address these limitations in practice, allowing for a better comparison of results.

Source: *See endnote 30 for this chapter.*


ESA/D. O'Donnell

UN Framework Convention on Climate Change, are the current compass guiding international and national policies aimed at reducing greenhouse gas emissions.[35] Similarly, the Convention on Biological Diversity, adopted in 1992, binds states to adopt national policies and action plans to preserve biodiversity and to promote fair and equal sharing of the benefits of genetic resources.[36] Among notable treaty successes, the adoption of the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987 and subsequent amendments resulted in a timeline and governing rules for countries to effectively phase out ozone-depleting substances, while establishing a fund to help developing countries with implementation.[37]

At the national and regional levels, examples of regulations that support sustainable economic activities include bans or restrictions on the use and release of toxic substances; limitations on forest clearing and overfishing; requirements for environmental impact assessments; labour standards; mandatory consultation and consent of affected communities; and mandatory due diligence and third-party verification of supply chains.[38] Authorities also may apply market instruments, such as pricing, to discourage products and activities that have negative environmental impacts (such as through carbon pricing) and to incentivise products and activities that are more environmentally beneficial (such as through subsidies, tax credits, labelling, etc.).[39]

The private sector, too, helps create normative rules through standards and certifications, such as the ISO 14001 standard that sets criteria for the environmental management of economic activities.[40] Similar initiatives exist for many industrial sectors, providing guidance to help companies comply with the standards and rules that apply to their activities.

IMPACTS OF ENERGY SYSTEMS ON THE ENVIRONMENT AND HUMAN WELL-BEING

Energy systems comprise the many elements and processes that enable the flow of energy along a pathway – from initial extraction and production, through transformation and distribution, to final end-use. Energy systems have been conceptualised as socio-technical systems because technical elements, such as power plants, grids, and distribution systems, are embedded in social and economic contexts. Policies, regulations, economic models, cultural practices, energy consumption patterns, and lifestyles are all part of and have an influence on energy systems.[41]

As with other infrastructure, energy systems have an impact on and are influenced by the environment and society along their value chains and lifetimes. Impacts can be positive or negative. Although the individual impacts of energy systems cannot be easily weighed against each other, the overall relative net impact of a system can be assessed along a continuum, where choices made in system design and implementation dictate the net impacts associated with resulting energy flows.[42]

This continuum of net impacts, both environmental and social, is dictated greatly by the nature of the energy source being used, and by how this choice is implemented, from the extraction of fuels and materials to final energy use. Impacts can vary widely. They include not only possible harms or benefits to the environment, but also economic and social consequences such as employment and income generation, and the equal or unequal distribution of these benefits – depending on how and in what context the energy system operates.[43]

Choices made along energy system pathways, from beginning to end, all dictate the aggregate outcomes – in terms of relative sustainability as well as relative impacts on human lives, human activities and the wider environment in which all life co-exists.[44]

The Fossil Fuel-based Energy System

The current dominant energy system is based on the extraction and burning of fossil fuels (and to a lesser extent on nuclear power). It has had – and continues to have – devastating consequences on both the natural environment and human well-being, playing a significant role in global climate change, pollution and biodiversity loss.[45]

Every year, 8 billion tonnes of coal, 4 billion tonnes of oil and the equivalent of 2.6 billion tonnes of fossil gas are extracted and burned.[46] Emissions of outdoor particulate matter from fossil fuel combustion were responsible for an estimated 1.2 million premature deaths in 2020.[47] Since 1970, around 6 million tonnes of oil have been released into the sea from tanker spills alone, harming marine and coastal ecosystems.[48] This estimate does not account for oil spills from offshore rigs (the largest spill, in 2010, released 700,000 tonnes) and pipelines (for which aggregated data are scarce).[49]

Fossil fuels are responsible for three-quarters of human-caused greenhouse gas emissions, which are released at every stage of the fuels' life cycle: extraction, processing, transport and combustion.[50] In 2022, the combustion of fossil fuels emitted around 35 gigatonnes of carbon dioxide (CO_2) into the atmosphere.[51] This is the equivalent, in one year only, of using up to 35% of the planet's total remaining carbon budget[i] that is required to maintain safe climatic conditions, according to estimates.[52]

Greenhouse gas emissions from fossil fuels are undeniably the main driver of climate change, which in turn is the leading cause of increasing extreme weather events such as droughts, fires, storms and floods. Such events have directly contributed to more than 2 million deaths since 1970 and have left in their wake uninhabitable lands, affecting people's homes and livelihoods.[53] According to one estimate, weather events attributed to climate change have led to costs totalling more than USD 4 trillion over the past half century.[54] Each year, an estimated 20 million people are displaced due to extreme weather events, and this figure is expected to increase sharply in the coming decades.[55]

These examples illustrate the devastating impacts that the fossil fuel-based energy system has on both the environment and human health, at all stages of its life cycle. They also point to the very high and often hidden economic costs.[56]

Fossil fuels are responsible for **75%** of global greenhouse gas emissions

20 million people are displaced each year due to **extreme weather events**

1.2 million premature deaths in 2020 **from fossil-fuel derived particulate matter**

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[i] The carbon budget is the maximum total CO_2 that is still possible to emit to keep global warming below 1.5°C warming compared to pre-industrial levels. As of 2023, the carbon budget is calculated to be between 250 gigatonnes (50% likelihood to reach the target) and 100 gigatonnes (83% likelihood to reach the target). See endnote 52 for this chapter.

Renewable-based Energy Systems

The evidence is clear: phasing out fossil fuels and deploying renewable energy[i] is not only essential, but is also the fastest and most cost-effective way to reduce greenhouse gas emissions and keep global warming within 1.5°C above pre-industrial levels.[57] A rapid transition to a renewables-based energy system, brings further benefits, such as improvements in air quality and human health, as well as socio-economic advancements in countries across the globe.[58] Given these wide-ranging benefits, an increasing number of countries recognise the deployment of renewables as a top priority. In Europe, under the latest revision of the Renewable Energy Directive, renewable energy deployment is presumed to be of "overriding public interest".[59]

Analysis from the International Renewable Energy Agency (IRENA) has compared the benefits of an ambitious energy transition scenario – one that is compatible with the 1.5°C climate goal[ii] – against the current "planned energy scenario", which reflects only governments' existing energy plans, targets, and policies, with a focus on the G20 countries.[60] IRENA's analysis aims to provide a holistic vision of the socio-economic impacts of the energy transition by considering a full range of economic, social, environmental, distributional and energy access factors[iii],[61] It finds that putting in place appropriate policies to reduce energy-related emissions through the adoption of renewables will yield global economic gains (increases in GDP and employment) as well as net gains for social welfare (improved health and education outcomes) and the environment (reduced emissions and material consumption).[62] However, the distribution of benefits will vary depending on policy choices, and "just transition" policies are needed to ensure gains for all regions and communities.

The deployment of renewable energy has provided a massive boost to employment, generating more than 12.7 million jobs globally as of 2021, and the employment potential from renewables far exceeds expected job losses in the fossil fuel industry.[63] Renewable energy also is delivering social benefits such as reduced energy costs, enhanced health, greater inclusivity, and improved energy security and access.[64] Distributed renewables, in particular, have proven effective in increasing energy access and alleviating energy poverty.[65] Renewables can be deployed in a diversity of settings and through many different business and (co-)equity models, allowing for greater energy security and energy sovereignty and for fairer distribution of benefits and burdens.[66] (► **See Energy Justice chapter.)**

The ability to deploy renewable energy rapidly enough to meet the world's decarbonisation targets is no longer merely a hopeful vision. Over the past decade, wind and solar energy systems have been installed globally at a faster pace than the International Energy Agency (IEA) envisioned in its scenarios for net zero greenhouse gas emissions, indicating that a timely and effective energy transition is possible.[67]

Unlike fossil fuels, most renewable energy technologies emit zero to few greenhouse gases during operation and do not require the use of finite and harmful fuels (► **see Ecosystems chapter for more on technologies)**. However, negative impacts can result from activities that occur at other stages of the life cycle of renewables. They include the displacement of communities to allow for the siting of new facilities and infrastructure; poor working conditions, pollution, and greenhouse gas emissions during manufacturing and along the supply chain of components; and the generation of hazardous waste during decommissioning. (► **See Materials chapter and Energy Justice chapter.)**

In contrast to fossil fuel-based technologies, most of the impacts generated by the deployment of renewables can be avoided or mitigated, provided that regulations and good practices are in place. Examining such impacts and identifying relevant mitigation measures is the focus of this report.

REPORT METHODOLOGY

Producing a report on the sustainability of renewables requires a holistic approach, not only content-wise, but also in terms of the perspectives consulted and reflected in the analysis. This has guided the methodological approach of the report, which follows REN21's reporting principles and is evidence-based and crowd-sourced (► **see Figure 3**).

To draw from the existing knowledge on renewable energy and its sustainability, REN21 first conducted an exploratory review of studies published by academia, industry, and non-governmental and intergovernmental organisations. This literature review provided a holistic understanding of the current state of knowledge, which served as a foundation for further analysis and helped identify key areas of focus for the report.

An Advisory Committee was established that includes experts from various stakeholder groups (non-governmental and inter-governmental organisations, academia and industry), with members coming from the perspectives of not only energy, but also environmental protection, human rights, finance and labour. This helped ensure that the research considered diverse viewpoints, including those of industry, policy makers and researchers.

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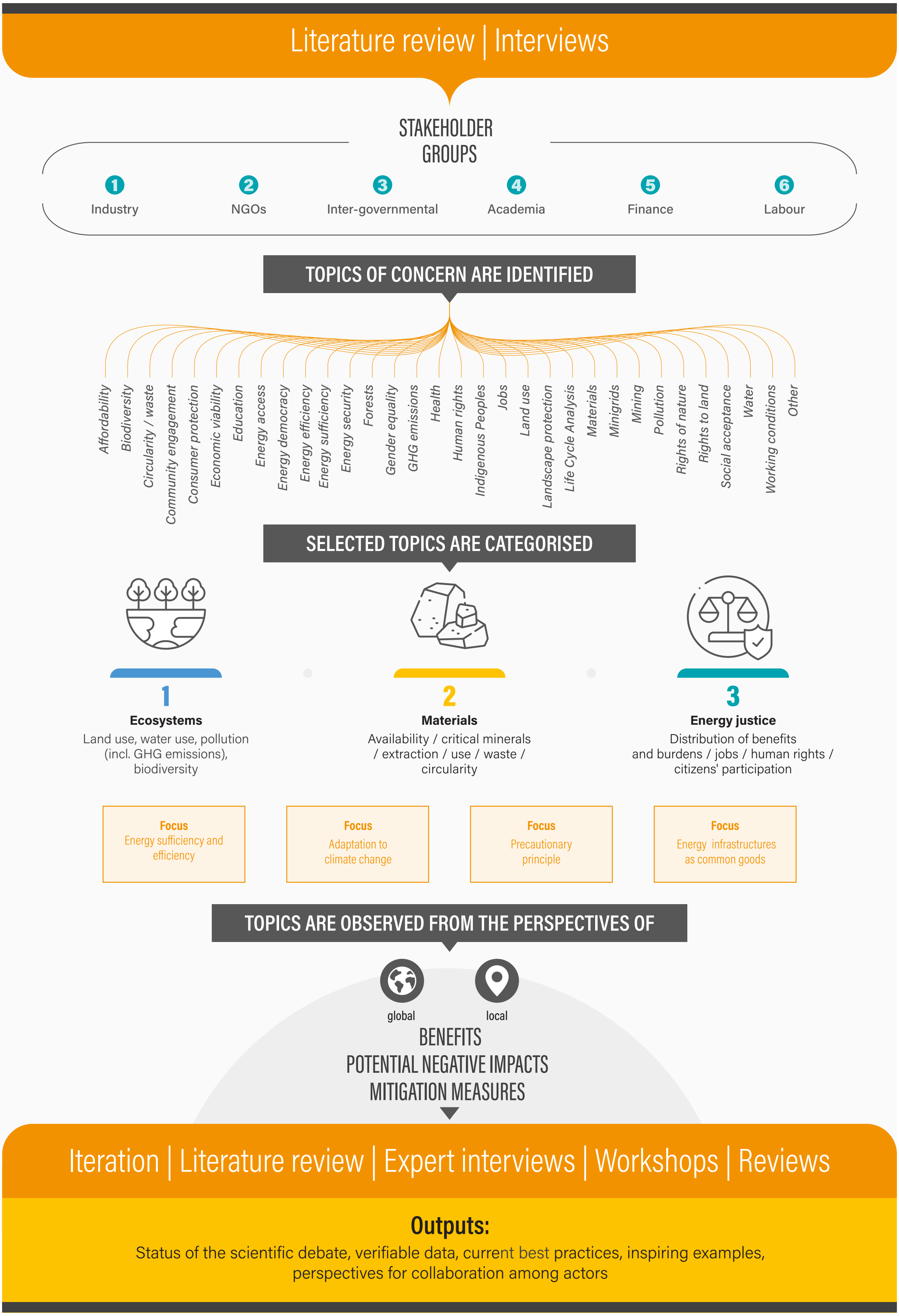
[i] Renewable energy is defined as any form of energy, from solar, geophysical, or biological sources, that is replenished by natural processes at a rate that equals or exceeds its rate of use. See endnote 57 for this chapter.

[ii] IRENA's 1.5°C Scenario describes a pathway for the energy transition that is aligned with the climate goal of limiting the increase in the global average temperature by the end of the 21st century to 1.5°C, relative to pre-industrial levels, while prioritising readily available technologies. See endnote 60 for this chapter.

[iii] In IRENA's Welfare Index, the indicators used to measure economic performance are gross domestic product, total employment, and consumption plus investment. The social welfare indicators include total (public and private) expenditure on education, as well as health improvements from reduced air pollution. The environmental benefits are measured through reductions in greenhouse gas emissions and material consumption (minerals and biomass). See endnote 61 for this chapter.

FIGURE 3. Methodology of the Report



GHG = greenhouse gas

REN21 also hosted a series of workshops that brought together experts from various backgrounds to discuss the framing, evidence and questions presented. In addition, REN21 conducted bilateral interviews with experts in the field to gather their opinions and insights. A questionnaire was made available to the wider REN21 community to collect further data for the report.

As a final step, REN21 facilitated multiple crowd-sourced expert reviews of the report's content to ensure that the findings and recommendations are grounded in the latest evidence and best practices. These reviews provided quality control and helped identify any research gaps or limitations. The results of the literature review, expert input and crowd-sourced feedback were used to produce the final report. This combination of methods helped ensure that the information presented in the report is balanced and reflects the latest knowledge and perspectives on renewables and sustainability.

Research Questions

The report is organised around two central questions:

1. Relative to the current fossil fuel-based system, what are the benefits, as well as the possible negative impacts, that the deployment of renewable energy brings for the natural environment and human well-being, both over the life cycles of renewables and throughout their supply chains?

2. How can stakeholders work together to avoid and mitigate the potential negative impacts, while maximising the benefits of renewables?

These questions are explored from three interlinked perspectives:

Ecosystems: What are the positive and negative impacts of renewables on the use of land and water resources; on air, land and water quality; and on biodiversity? For example, how can a healthy biodiversity co-exist with the rapid scale-up and deployment of renewables, and in what ways can renewables have positive impacts on biodiversity and on Earth's ecosystems? How do renewables contribute to mitigating climate change, and how are they affected by it?

Materials: What are the materials used for different renewable energy technologies? Which materials are deemed critical, and what are potential solutions to reduce their use? How can circular approaches help reduce materials use? What are challenges and potential solutions for the uptake of circular supply chains? What is the balance between supply and demand for the materials needed for renewables deployment? Are enough materials available to supply renewable energy industries at the pace needed to fulfil climate objectives? Where and how are materials sourced, and what are ways to minimise the impacts of these extractive and manufacturing activities on the environment, economies and societies?

Energy Justice: What are the urgent social and economic implications of the renewable energy transition, and how can they be addressed? How do we ensure that the benefits of the transition are fairly distributed, that the burdens are not overwhelmingly held by the most vulnerable, that human rights are respected along the value chain, and that all stakeholders have a voice?

These questions cannot be answered with a simple binary response, nor is it possible to quantify all impacts. This report strives to provide the most accurate picture yet of the opportunities and challenges associated with the deployment of renewables, and of the many solutions being advanced to avoid and mitigate negative impacts. The report explores and draws lessons from a wide range of renewable energy projects around the world.

Scope of This Report

The RESR aims to provide a first overview of the environmental, social and economic sustainability of renewable energy technologies. Although it covers a wide range of topics, it cannot provide in-depth analysis of all of them. The report focuses on key renewable energy sources, and certain technologies such as hydrogen and heat pumps, and rail electrification, are not covered. The report does not propose any further standards, guidelines or scenarios (► see Sidebar 1); instead, it strives to describe the diversity of options already in use or proposed.[68] Throughout this report, examples of the diverse regulations, standards and certifications that relate to renewable energy technologies and infrastructure (in both the private and public sectors) are provided to highlight ways to maximise the benefits of renewables and minimise the potential negative impacts.

During the research, a significant lack of consolidated data on certain topics related to the sustainability of renewables became apparent. Meanwhile, the acceleration of renewable energy deployment, technological innovation, and rising awareness of the importance of deploying renewables in a sustainable manner lead to the continuous development of new approaches, initiatives and solutions.

The report relies where possible on the latest available information and data, with a defined cut-off date of April 2023 and some additions through August 2023.

Continuously capturing new developments and broadening the scope of coverage and analysis could be the focus of future research.

Sidebar 1. How Much Renewable Energy Will We Need?

As the world moves forward with large-scale deployment of renewables, how do we know how much capacity or generation – and of which technologies – need to be deployed to decarbonise the global energy system?

Diverse players in the energy field have explored and published scenarios for the energy transition at the global, regional and local levels. These stakeholders include, among others: intergovernmental organisations such as the IEA and IRENA; consultancies such as McKinsey and BloombergNEF; the biggest fossil fuel industry players such as Shell and BP; and national transmission system operators. Academic and civil society organisations also have proposed pathways for a renewables-based energy system – such as the University of Technology Sydney, the PAC consortium within the European Union (EU) and the developers of the negaWatt scenario in France.

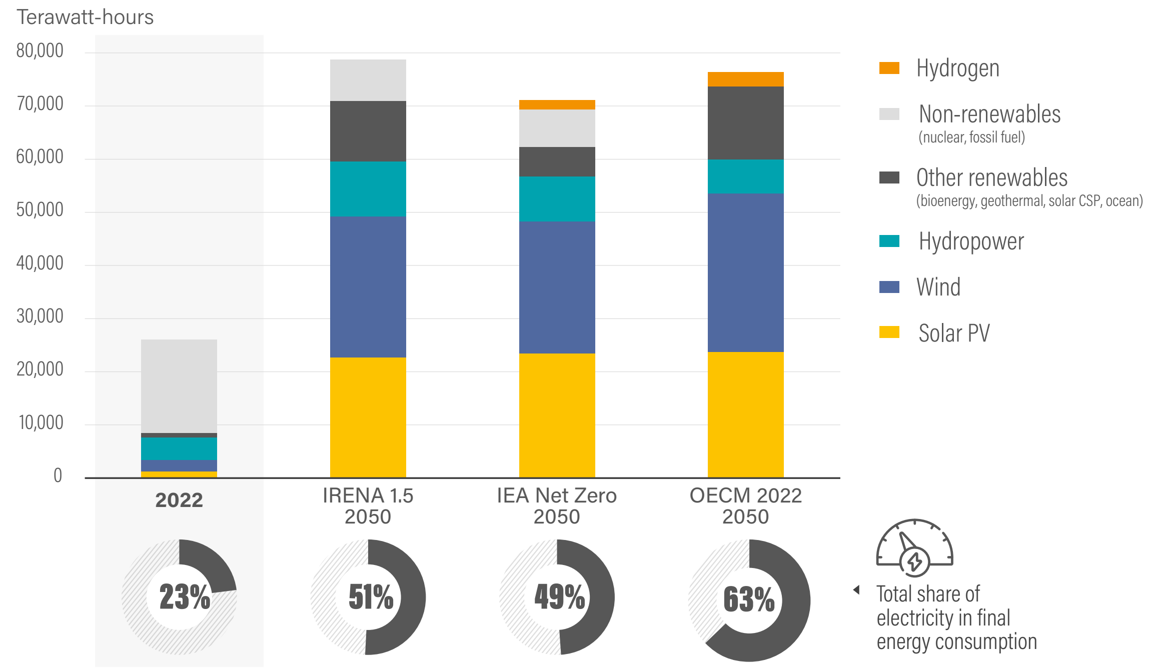
Such scenarios highlight different potential pathways to achieve specified reductions in greenhouse gas emissions, and some but not all include energy sources beyond renewables. The outcomes of these scenarios hinge on different projections for reducing energy demand through energy efficiency and sufficiency (**► see Special Focus 1, p. 28**), as well as on different technology mixes, not only for energy generation but also for networks and storage. For example, scenarios for decarbonising the global energy system by 2050 assume a total final energy consumption level ranging from around 300 exajoules (EJ) to more than 500 EJ.

Not all scenarios propose a mix of 100% renewables as the endpoint, nor do they all assume the same degree of electrification of the energy system (► see Figure 4). Some scenarios rely heavily on technologies such as hydrogen and carbon capture and storage to reduce emissions, whereas others focus more on demand-side measures such as the role of lifestyle and behavioural changes to reduce final energy consumption.

All scenarios rely on specific assumptions that would be necessary for the different pathways to occur. These include assumptions around investments and policies, weather conditions, supply capacities and workforce skilling. In practice, the scale, place and timeline of deployment of each renewable energy technology is dependent on whether or not these assumptions are realised at both the local and the global scales.

This report focuses on the objective of transitioning to an energy system based on renewables. In line with scenarios centred on this goal, the analysis is undertaken with the assumption that a substantial increase in renewable energy, alongside widespread electrification and a reduction in total final energy consumption through energy efficiency and energy sufficiency, will be necessary in the years to come.

FIGURE 4. Electricity Generation by 2050 Under Three Scenarios, and Comparison with 2022



Note: IRENA 1.5 °C scenario, IEA Net Zero Scenario, OECM: One Earth Climate Model (University of Technology Sydney)

Source: *IRENA, IEA and UTS. See endnote 68 for this chapter.*

SPECIAL FOCUS 1.
ENERGY SUFFICIENCY

THE CONTINUED GROWTH in global energy demand can severely restrict the positive impacts of transitioning to renewable energy generation. Because of the challenges of decoupling energy demand from economic growth, it remains very difficult to limit greenhouse gas emissions within a "safe climate operating space for humanity". While renewables are essential to reduce emissions, they will still have environmental impacts, and the higher the demand for energy, the greater these impacts will be. Reducing global energy consumption is therefore a key priority for sustainability, and a vital context for any debate on the sustainability of renewables.

Traditionally, reduction in energy demand has been pursued mostly under the banner of energy *efficiency* – "changes in the amount of energy used to provide a given level of services" – which assumes little change in economic activity. Efficiency measures focus on technological and infrastructure changes, and include actions such as housing retrofits, using LED lights and driving less fuel-intensive cars. The fundamental activities do not change, but the amount of energy required does. However, there is increased focus on energy *sufficiency*, which emphasises reducing demand through "changes in the level of services that use energy". While both approaches are needed, they lead to very different responses. In contrast to efficiency, sufficiency measures focus on reduction in energy use through behavioural and system changes, such as lower meat consumption or shifting to active travel.

Such an approach has varied implications for the environmental, social and economic pillars of sustainability. In particular, it raises issues about social welfare and justice, as well as questions about conventional economic models, especially the reliance on consumerism rather than meeting basic needs. Thus, a sufficiency approach leads to demands for more transformative social change.

History and Contemporary Relevance

The principles of energy sufficiency evolved from the ideas of energy conservation that became prominent in response to the oil price shocks of the 1970s, as governments encouraged restraint in energy use, such as rationing of fuel. During the 1980s, energy conservation was gradually replaced by energy efficiency in policy documents and measures, as this aligned more closely with the predominant objective of economic growth.

More recently, amid the climate crisis, there has been growing interest in the potential of energy sufficiency, with proponents in Europe that include the Wuppertal Institute in Germany and the European Council for an Energy Efficient Economy. In particular, questions have been raised about the efficacy of energy efficiency due to rebound effects. There is concern that efficiency does not always lead to reduced consumption because the cost or other savings (e.g., time) allow the user to consume more or different energy-expending services. An example would be a driver who replaces a car with a fuel-efficient model, only to take advantage of its cheaper running costs to drive farther. In contrast, sufficiency is seen as more promising because it focuses on overall energy reduction.

One perspective on this is degrowth (or post-growth). This has origins in the Club of Rome's *The Limits to Growth* and emphasises that sufficiency does not equate to a reduction in welfare, but rather to reductions in consumption, with the view that a change in economic approach can bring about greater human flourishing. This highlights the need to reduce resource input into economic activities; it therefore has links to circular economies and self-sufficiency, and has found expression in the idea of degrowth in cities, with experiments in cities such as Roubaix in France and Leipzig in Germany.

Case Examples and Illustrative Issues

Energy sufficiency measures can be understood from two perspectives: bottom-up, voluntary *behaviour changes of individuals and communities*, and *systemic change* that enables and incentivises widespread changes in behaviour.

In terms of *individual behaviour change*, while governments can encourage change through information campaigns or economic incentives, the most effective shifts in behaviours come from the individual. Here, tools such as a carbon footprint or a Greenhouse Gas Equivalencies Calculator can help inform action. *Community-based approaches* also can drive sufficiency behaviour, by reducing the sense of marginalisation among early adopters. while community-based initiatives also "tend to speed the diffusion of new social norms".

In France, the Colibris movement, now involving 250,000 people through social networks, defines itself as a movement of "individuals who invent, experiment, and cooperate concretely to build shared lifestyles that respect nature and people". Part of the movement's focus is on "joyful sufficiency", and sufficiency initiatives are shared and supported through an online platform. Community renewable energy generation and microgrids also can engender self-sufficiency and collective self-restraint. For example, a community energy project in the rural Welsh community of Machynlleth combined "local financial participation and energy sufficiency, targeting and challenging given patterns of unsustainable consumption".

Top-down *structural changes* require more fundamental government action, such as public investments in infrastructure to encourage a modal shift from private automobiles to public transport, cycling and walking; flight rationing; localisation of economic activity and supply chains through restrictions or tariffs on imported goods that can be produced locally; introduction of four-day work weeks requiring less energy consumption in office buildings; and regulations to limit the floor space of housing to prevent lack of wasted energy heating.

In its Sixth Assessment Report, the Intergovernmental Panel on Climate Change describes sufficiency policies as "a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries".
In the long term, sufficiency highlights that alternative economic models can prioritise prosperity over growth.

Source: *See endnote 69 for the Introduction chapter.*

02

ECOSYSTEMS

02

ECOSYSTEMS

INTRODUCTION

Life on Earth depends on healthy ecosystems.[1] Well-functioning natural systems, including a stable climate and rich and enduring biodiversity, are the foundations of our economies and of human well-being.[2] We rely on the natural environment for resources – food, clean air and water, medicines and materials – as well as for services, including climate regulation and protection from natural disasters and disease.[3]

Today, all life is under pressure due to the impacts of human activities on the environment. This includes direct effects such as pollution of the air, soil, and water, and excess emissions of CO_2 and other compounds, which result in global climate change. In turn, pollution and climate change are driving further degradation. They are disrupting large-scale atmospheric and oceanic processes, increasing the severity and frequency of extreme weather events, altering interactions among species, causing biodiversity loss, posing risks to food and water availability, and threatening human health and safety.[4] Human inputs in the global biosphere have cascading effects and feedback loops across all interconnected systems.

The primary driver of such changes is our unsustainable production and use of fossil fuels.[5] The extraction, transport and processing of fossil fuels disturb and degrade ecosystems and contribute to pollution of the air, soil and water.[6] The combustion of fossil fuels is responsible for most of the world's air pollution and is a major source of greenhouse gases and other pollutants that drive climate change and threaten human health.[7]

Reducing energy demand and using renewable energy sources to displace fossil fuels can reduce pollution, contribute to climate change mitigation, help combat biodiversity loss and improve human health. There is robust international consensus that rapid and significant expansion of renewable energy is urgently needed.[8] However, no energy generation technology is without environmental risks and potential impacts. The manufacture, construction, and operation of energy infrastructure, including renewables, requires natural resources (minerals, water and land) and can cause pollution and impact biodiversity.

The nature and scale of the resource demands and environmental impacts associated with energy provision and infrastructure vary depending on the technology and deployment methods, among other factors. Renewable energy is proven to have clear advantages over fossil fuels, and the potential impacts of renewables can be mitigated, or even eliminated, by following good practice guidelines and adopting available solutions. As the energy transition gathers pace, innovative new solutions are developing rapidly. For example, solar PV technologies have the potential to integrate seamlessly into existing infrastructure


DFID - UK Department for International Development

or into already polluted and degraded lands, and bioenergy projects can generate energy from agricultural and forestry waste and landfill methane.

> ✓ Unlike fossil fuels, the potential negative impacts of renewables can be avoided or mitigated by following good practices and adopting available solutions.

This chapter aims to shed light on the potential for both positive and negative interactions between renewables and Earth's ecosystems, providing insights into the environmental dimensions of renewable energy systems and highlighting ways to maximise the benefits. In the first part, renewables and fossil fuels are compared generally, while the second part delves deeper into each technology. Both parts are structured around four key themes: land use, water use, pollution and greenhouse gas emissions, and biodiversity. A final summary table outlines potential impacts and the corresponding mitigation measures.

ENERGY SYSTEMS AND EARTH'S ECOSYSTEMS

Key indicators of pressures on Earth's ecosystems include land use, water use, greenhouse gas emissions, and air, soil and water pollution – all of which affect ecosystems and biodiversity. The impacts of renewable energy in these areas can be minimised when renewable technologies are deployed according to well-documented good practices. This includes systemic measures such as impact assessments, integrated planning and mapping, and adaptive management.[9] Technology solutions and site- and size-specific measures exist to prevent and mitigate direct impacts at the project level.

Renewable energy deployments can co-exist with other activities, such as agriculture, as well as add value to existing infrastructure and degraded land. Renewables also can bring a host of other co-benefits, such as job creation and investment in local value chains. However, calculations of resource demands and impacts related to renewables vary widely, as a plethora of approaches are available for assessing each technology.[10] Ongoing research on life cycle analysis aims to further harmonise approaches.[11]

Land Use

Half of the world's habitable land[i] is used for agriculture[ii] (76% of which is dedicated to raising livestock), and 31% is forested[iii] (22% managed forests and 9% primary forests) (► **see Figure 5**).[12] Human infrastructure (settlements, mining, etc.) occupies just 1% of the land area, with one study estimating that the global energy system occupies 0.4% of the planet's ice-free land.[13]

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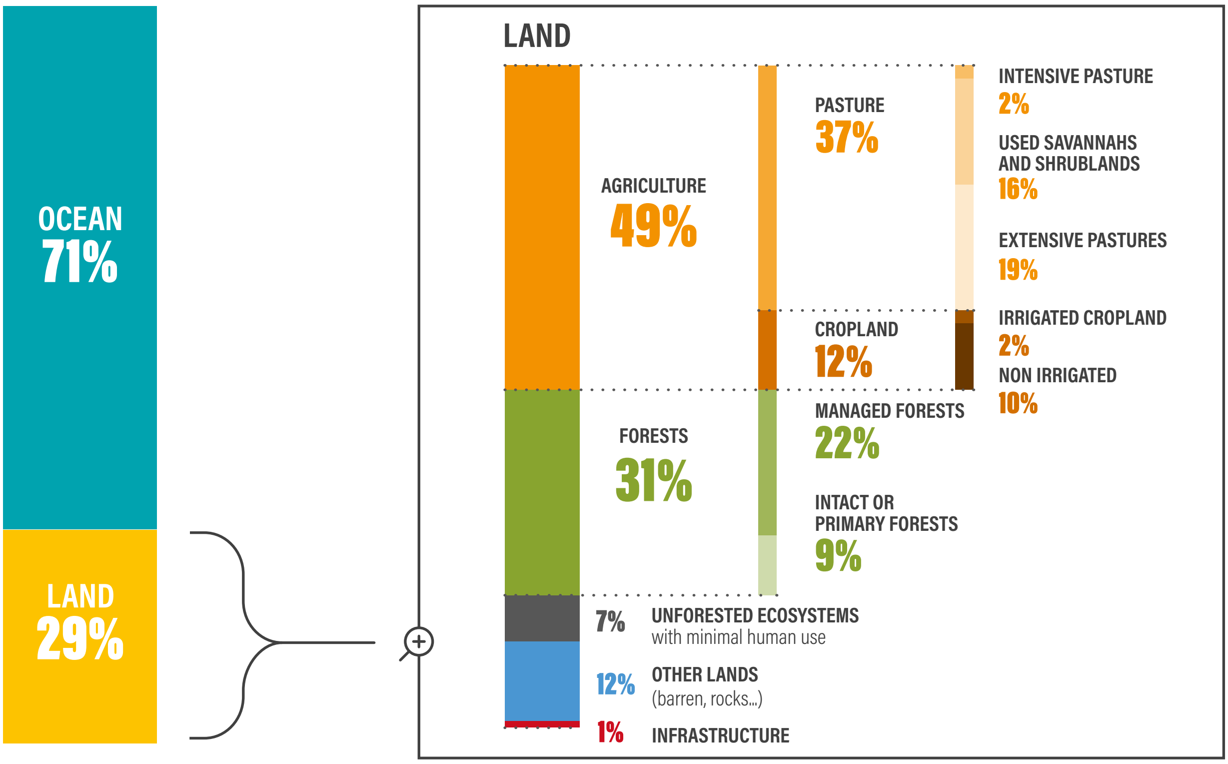
[i] "Habitable land" excludes the 10% of the Earth covered by glaciers and the 19% that is "barren" (deserts, dry salt flats, beaches, sand dunes and exposed rocks).
[ii] This includes the combined area of pastures used for grazing and land used to grow crops for animal feed.
[iii] Note that crop lands and forest lands are also used for production of bioenergy.

FIGURE 5. Distribution of Global Ice-Free Land Area, as of 2015



Source: *IPCC. See endnote 12 for this chapter.*

The human population is projected to grow from 8 billion in 2022 to 10 billion by 2050, bringing increased food requirements, urbanisation, industrialisation and energy demand.[14] These factors are expected to lead to greater competition for land, resulting in rising conflict and necessitating difficult trade-offs between land uses and environmental impacts.[15] These issues will be exacerbated by the impacts of global heating, as intensifying droughts and floods, sea-level rise, and extreme weather events trigger further changes in land use.[16]

The land-use intensity of different energy generation technologies can be defined as the land area required annually per unit of energy production – measured, for example, in hectares per terawatt-hour (TWh). Direct land use is the area needed for the infrastructure of the facility itself, while indirect land use may encompass the additional area needed to mine, process, refine, and transport materials and fuels; as well as factory space, supporting infrastructure and spacing areas (such as between wind turbines).[17]

Estimates of the land use of energy production vary considerably depending on the calculation method used and on the scope of demands included (► see Figure 6).[18] A coal-fired power station may appear to have a small footprint if the land requirements for mining and processing coal are not considered, and the footprint of an individual wind turbine is minimal; however, an entire wind farm could seem to cover a much larger area, if calculations include access roads and land for spacing and do not account for other uses of that land.[19]

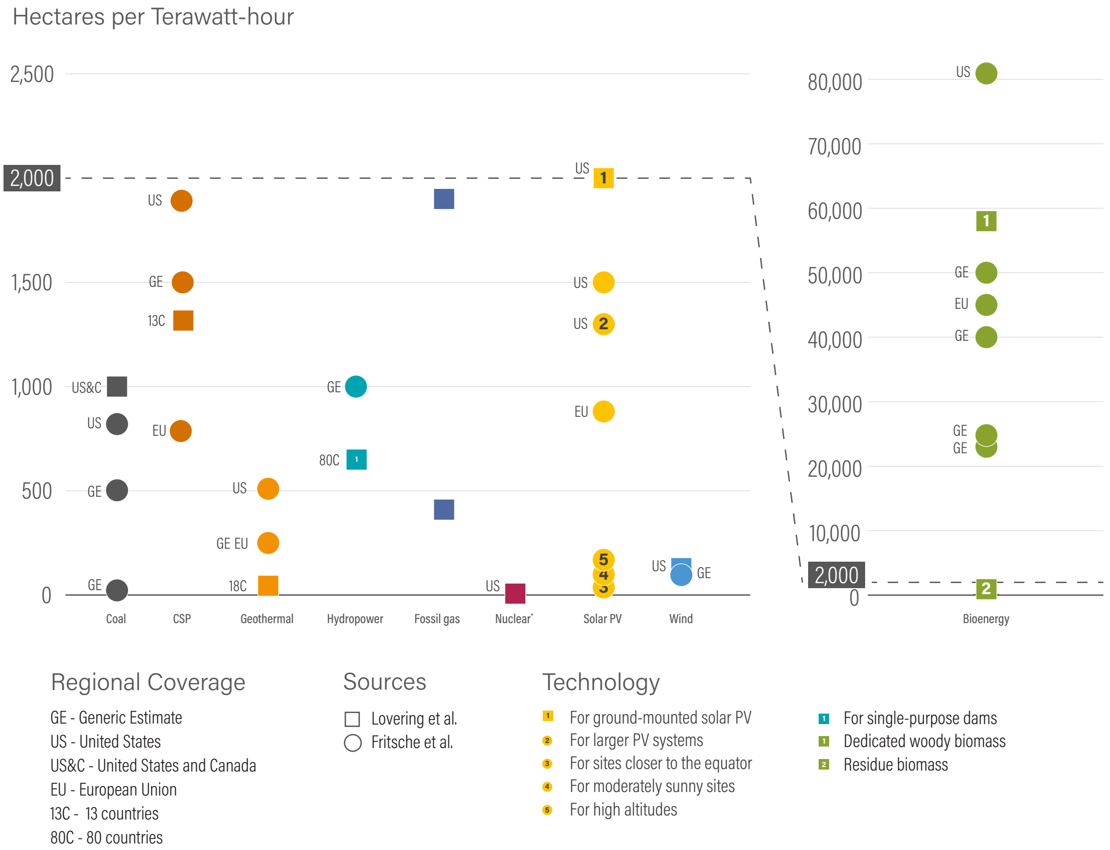
Time variables, although rarely considered in land-use calculations, are also important. Whereas renewables can use the same land area for years, fossil fuel extraction requires continual exploration, drilling and mining of new areas.[20] Fossil fuel facilities often leave land polluted and degraded long after the sites are decommissioned.[21]

Land Use: Fossil Fuels and Nuclear Power

Land-use estimates for fossil fuels and nuclear power vary widely. The footprint calculations for fossil gas range from 410 to 1,900 hectares per TWh, and for coal from 20 to 1,000 hectares per TWh, depending on the type of coal mine.[22] Such estimates can be deceptive given the challenges of including the full range of land-use impacts, as fossil fuel activity can ultimately occupy or degrade vast land areas.

Some coal extraction methods, such as mountaintop removal, remodel entire landscapes, destroying the soil and pushing out plants and animals.[23] Underground coal mining has a lower land-use footprint than open-surface mining but can impact land in other ways, such as through subsidence and groundwater contamination.[24] In many regions, entire towns have been demolished to make way for coal mines, and in other places land that could be used for rural expansion may be consumed by mining before other possibilities can be explored.[25]

FIGURE 6. Estimated Land-Use Intensity of Different Energy Generation Technologies



Note: Nuclear power land-use calculations do not account for nuclear waste storage or eviction zones after accidents. For wind energy calculations, the space between the turbines is are not included, as this space can be used for other purposes.

Land-use intensity is defined as the land area required annually per unit of energy production, measured in hectares per terawatt-hour (TWh). Calculations of land-use intensity per technology vary according to the context, the technologies deployed and the calculation methods.

Source: *See endnote 18 for this chapter.*

Accidental spills, dumped waste and chemical-infused wastewater from oil drilling pollutes waterways and soil, damaging agricultural and pasture land.[26] Construction of oil pipelines, roads, drilling sites and other infrastructure can destroy large areas of wilderness, while the human health impacts of oil extraction can effectively render the land uninhabitable.[27]

For nuclear power, a US study[i] suggests a median land-use footprint of 7 hectares per TWh per year, including direct impacts from power plants and indirect impacts associated with mining and processing of fuel.[28] Calculations usually omit the disposal of radioactive waste. France is home to an estimated 1.7 million cubic metres (m^3) of nuclear waste, with three-quarters of it stored in dedicated public facilities[ii,29] A planned storage facility with an underground surface area of around 250 square kilometres is expected to receive less than 5% of France's existing stock once complete.[30] In the United States, the cancelled Yucca Mountain waste repository would have added up to 2.9 hectares per TWh to the land-use intensity of nuclear power.[31] Accounting for accidents would further increase the land requirements for nuclear power by around 4 hectares per TWh per year.[32]

> Land use is context-specific, and calculations should be considered with care. Many renewable energy technologies can co-exist with other uses and support conservation and restoration.

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i The United States uses a relatively larger land area per unit of energy than other countries (owing to geographical characteristics and limited economies of scale), and the country mines almost no uranium; thus, these estimates may not be accurate for other jurisdictions.

ii The remaining quarter is stored on-site.

Land Use: Renewables

A variety of planning and deployment pathways for sustainable energy production exist that simultaneously address land-use challenges, add value to deployment sites and minimise environmental impacts. Many renewable energy technologies – such as solar PV, wind power and hydropower – can co-exist with other activities, reducing the need for additional land.

Solar PV panels or solar thermal systems can be integrated into existing infrastructure, such as on rooftops or building façades, where they can generate energy at or near the point of consumption.[33] By maximising the use of available space on buildings, such systems can avoid the need for new land and provide localised energy access and participation.[34] Agrivoltaics integrates solar panels with agricultural operations: solar panels placed above or amid crops provide shade, reduce water evaporation and improve the microclimate for plant growth. Wind turbines can be used in conjunction with activities such as ranching and farming, and micro-turbines can be installed on buildings.

Renewable technologies such as solar PV panels and wind turbines can be installed along existing transport and transmission corridors, while former industrial areas and brownfield sites can be revitalised by renewable energy deployment, granting the land a new purpose and remediating the legacy of industrial activities. Dry, sunny desert landscapes, often inhospitable for conventional land uses, can be prime locations for large-scale installations of concentrating solar thermal power (CSP). Renewable energy technologies also can leverage waste streams for energy generation, for example by producing biogas from organic waste or landfills.


Raphael Pouget / Climate Visuals Countdown

✓ Most renewable energy technologies can be deployed together with other activities, reducing the need for additional land.

Even so, renewable energy technologies require land both for the facilities themselves and for the expansion of supporting infrastructure (which is often omitted from calculations).[35] Direct land-use changes can occur, such as if land is cleared or converted to accommodate renewable installations or to grow bioenergy feedstocks.[36] Inappropriate deployment of ground-mounted technologies could exclude other users or lead to indirect land-use changes.[37] Land use and land-use changes related to energy also have impacts on natural resources, species and livelihoods. These impacts can be greatly reduced by following established good practices in project design and deployment.

Given the urgent need to restore soil health, the impact of energy systems on soil quality must be considered.[38] Fossil fuel operations and their extraction sites leave land polluted, degraded[i] and depleted long after the facilities are decommissioned.[39] Renewables are not prone to the same long-term impacts, and, as noted, many technologies can co-exist with other uses and support conservation and restoration.

Water Use

Just 3% of the Earth's water resource is fresh water, and only 0.5% of this is accessible.[40] The majority of fresh water is either frozen in ice caps and glaciers or too deep to be extracted.[41] Areas around water bodies continue to serve as socio-economic hubs, facilitating diverse activities such as agricultural production and energy generation. Governments have committed to ensuring universal access to safe and affordable drinking water for all by 2030, improving water quality and efficiency, implementing integrated water resources management, and protecting and restoring water-related ecosystems.[42]

Competition for access to water resources is intensifying as global demand increases for drinking water, irrigation, industry, energy production and mining (► **see Figure 7**).[43] At the current rate of extraction, by 2030 the global demand for water will exceed

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[i] Degraded land is land for which the ecological, biological, or economic condition has deteriorated, or where a loss in productivity has occurred due to direct or indirect human-induced processes.

supply by an estimated 40%.[44] This will exacerbate conditions in areas already facing water scarcity and stress[i]. Changes in water supply can directly impact the economy, with some regions expected to incur a loss in GDP of up to 6% by 2050.[45] Water scarcity also can lead to conflicts over shared resources.[46]

Water availability varies based on geography, climatic conditions and use rate. The relative availability, quality and quantity of water worldwide are important factors in understanding the water-energy nexus.[47] Water is required in many stages of the energy value chain, including extracting and refining raw materials, processing and transporting fuels, cooling thermal plants, and cleaning solar panels and wind turbines.[48] Water also is critical for hydropower production and for irrigating some bioenergy crops.[49]

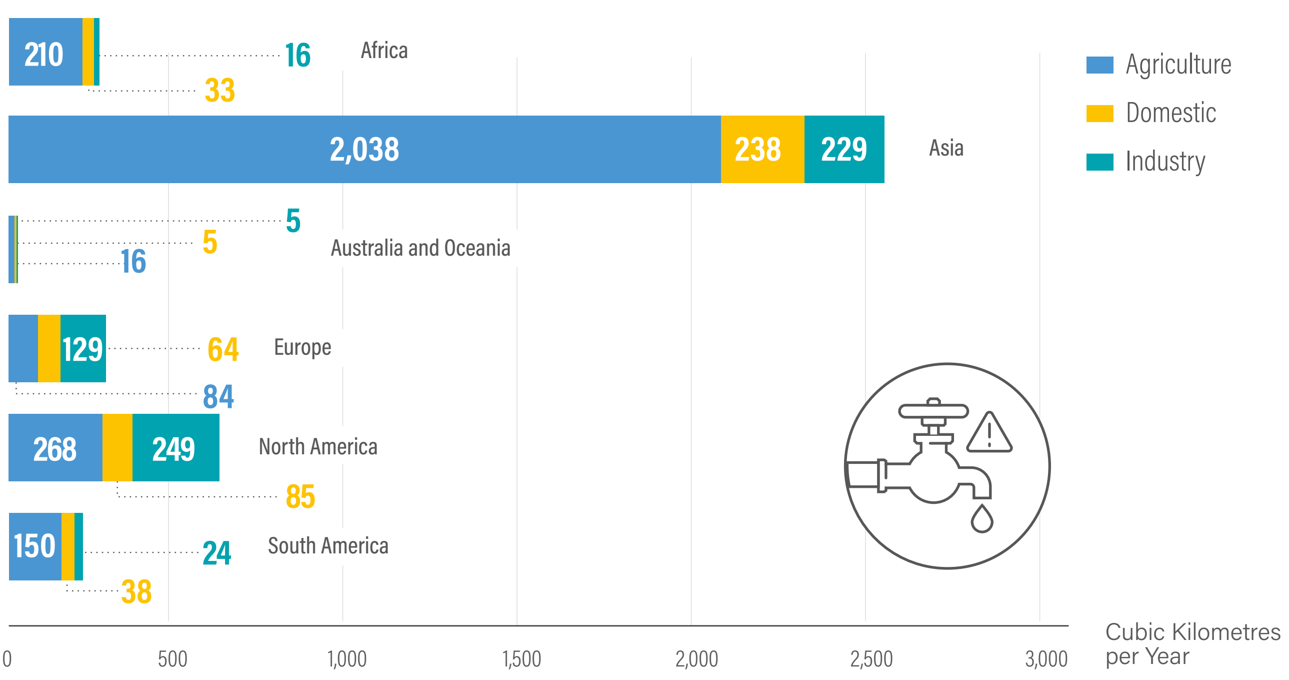
Globally, the energy sector uses an estimated 10% of the total water withdrawn and 3% of the total water consumed[ii].[50] As much as 44% of the water abstraction[iii] in the EU is used for energy production, mostly to cool thermal power plants.[51] Electricity and heat production account for an estimated 4% of the global annual consumptive water footprint[iv].[52]

Data on energy-related water footprints are limited, with significant variations or even contradictions among estimates.[53] Global assessments often extrapolate data from the United States, which do not effectively account for regional or local factors.[54] Water use estimates vary based on geography, climate, sample locations and myriad other factors. Caution should be taken even when comparing data for the same region, as results may vary depending on the methodologies used. To adequately capture the impact of energy deployment on water resources, and vice versa, more data collection and harmonisation are needed.[55]

> In the fossil fuel industry, water is required at all stages of drilling, extraction and processing of the fuels. Thermal power plants use water for cooling during operations.

A global meta-analysis suggests that the cooling technology being used influences water use more than the type of power being generated.[56] For coal, fossil gas, oil, nuclear, and biomass, power plants with closed-loop cooling technology are the largest water consumers; in particular, plants with once-through cooling technology are leading water withdrawers.[57] For CSP and geothermal, water withdrawal has widely been assumed to be equal to water consumption at the operational stage.[58]

FIGURE 7. Annual Freshwater Withdrawals by Continent and Sector, 2017



Source: *UN Water. See endnote 43 for this chapter.*

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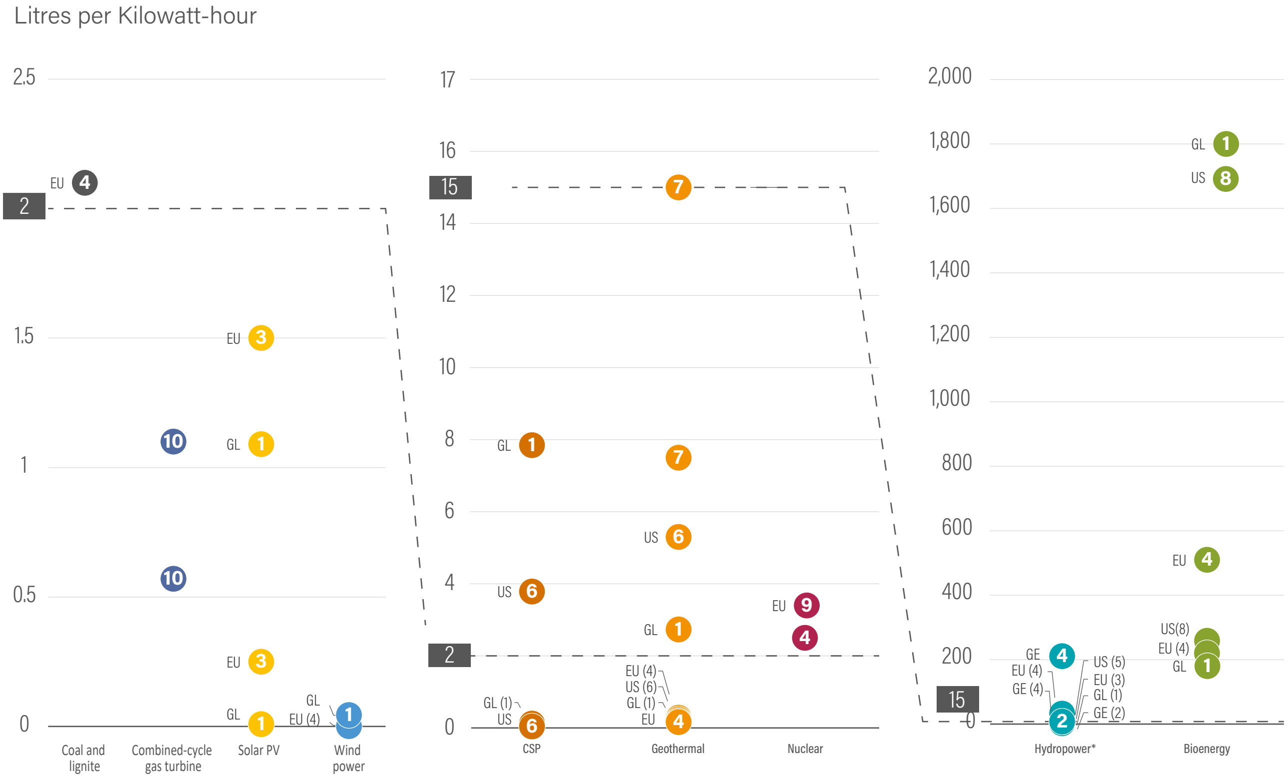
i Water stress occurs when demand surpasses availability.
ii Water withdrawal is the total amount of water taken from the source. Water consumption is the total volume of water that is used and not returned to the source.
iii Nearly all water that is abstracted (extracted from a natural source) for electricity generation is returned to a water body.
iv The water footprint is the amount of water that is consumed to produce a unit of energy during the entire value chain. The "consumptive water footprint" is the sum of the green water footprint (the volume of rainwater consumed) and the blue water footprint (the volume of surface and groundwater consumed).

FIGURE 8. Estimated Water Footprint of Different Energy Generation Technologies



Regional Coverage

GL - Global
GE - Generic Estimate
US - United States
EU - European Union

Sources

① Mekonnen et al. (2015)
② Bakken et al. (2013)
③ Stolz et al. (2018)
④ Vanham et al. (2019)
⑤ US Department of Energy (2006)
⑥ Mielke et al. (2010)
⑦ UNEP (2016)
⑧ Gerbens-Leenes et al. (2009)
⑨ Stolz et al. (2017)
⑩ IEA (2012)

Note: Estimates are converted into litres per kilowatt-hour from the sources. For hydropower, extreme values from Bakken et al. that do not account for multiple uses of reservoirs are not included.

Source: See endnote 67 for this chapter.

Water Use: Fossil Fuels and Nuclear Power

The use of fossil and nuclear fuels for energy production involves substantial water usage. Water is required at all stages of drilling, extraction and processing of the fuels. Thermal power plants use water for cooling during operations, often drawing from local water bodies such as rivers and lakes.

A life cycle analysis suggests that coal-fired power plants require on average 2.1 litres of water per kilowatt-hour (kWh).[59] Combined-cycle gas turbines have comparatively lower water demands than coal-fired plants, requiring between 0.57 and 1.1 litres per kWh on average.[60]

Nuclear energy requires water to extract and process fuel, produce electricity, control waste, cool components and manage operational risks.[61] Compared to other thermal power plants, nuclear plants generate steam at lower temperatures and pressure; this reduced thermal efficiency requires more cooling water per unit of electricity.[62] The average life cycle water footprint of a nuclear power plant is 3.4 litres per kWh.[63] Nuclear plants using the most common cooling methods increasingly face complicated siting procedures or expensive retrofits to comply with water regulations.[64]

Fossil fuels and nuclear energy indirectly affect the water cycle. Water expelled from nuclear plants and oil and gas wells can have a much different temperature and salinity compared to surrounding water bodies, which can negatively impact groundwater and soil quality.[65] Further groundwater contamination arises from spills or leaks of mine water that contains chemical products and residual hydrocarbons and, in the case of uranium mining, also radioactive wastes.[66]

Water Use: Renewables

Solar PV, wind power and run-of-river hydropower consume relatively little water, while CSP and geothermal consume intermediate volumes (► see Figure 8).[67] Both bioenergy and hydropower can entail significant water usage, although these technologies also have the largest variability; thus, local data are critical for understanding potential resource demands and appropriate siting and deployment.[68]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Pollution and Greenhouse Gas Emissions

Fossil fuels are responsible for most of the world's human-caused greenhouse gas emissions.[69] In 2022, the average global temperature was already 1.15 degrees Celsius warmer than during pre-industrial times, largely driven by the combustion of fossil fuels.[70] These fuels also pose threats to human health, with the entire global population now breathing poor-quality air.[71]

To fully compare the climate impacts of different energy technologies, estimates of the indirect emissions per unit of energy output must be considered. This includes emissions associated with the extraction, processing, and transport of fuels, as well as with combustion. This kind of analysis relies on life cycle assessments of emissions to generate an emissions intensity for each fuel.

Pollution and Greenhouse Gas Emissions: Fossil Fuels and Nuclear Power

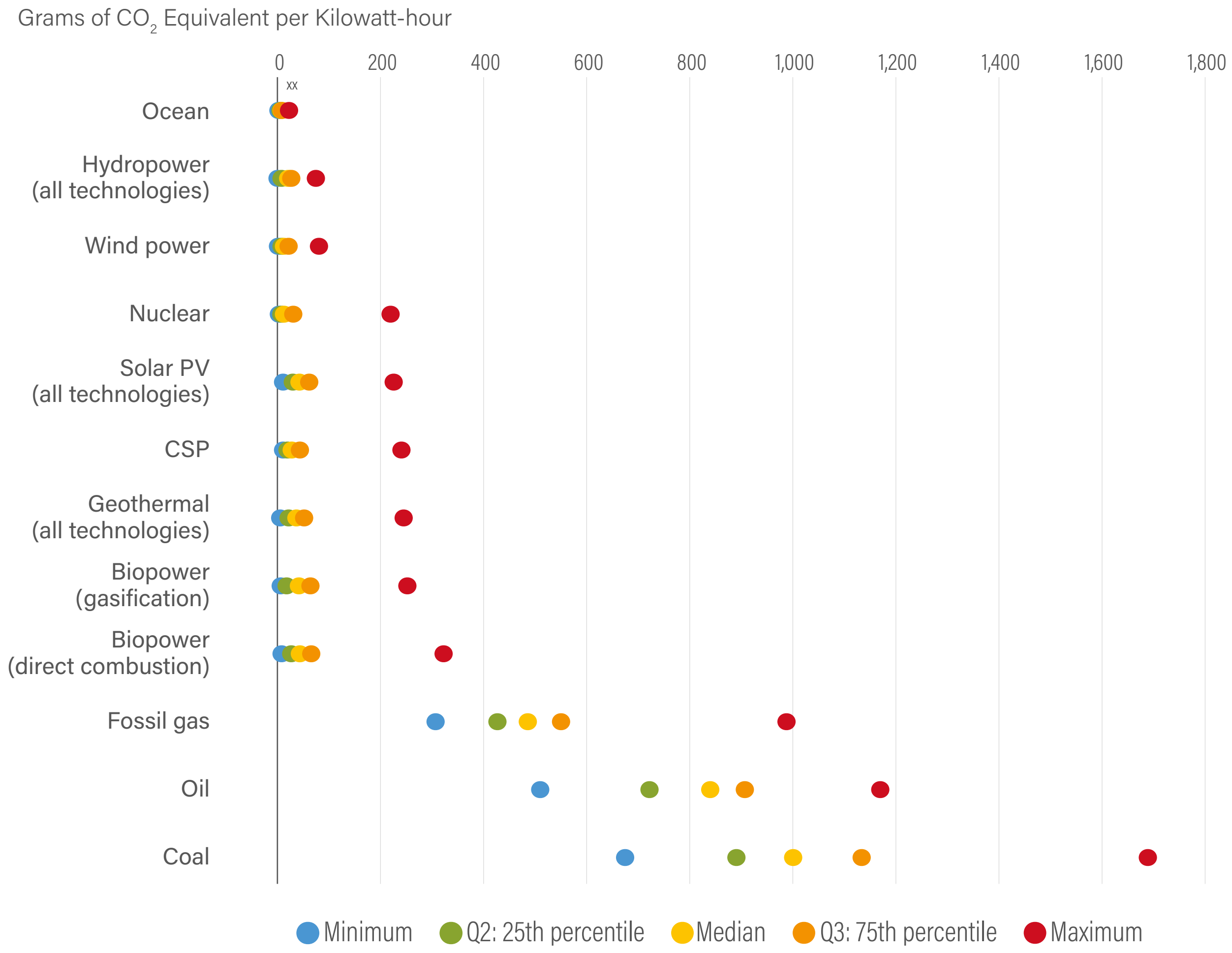
Fossil fuel energy generation results in CO_2 emissions and harmful air and water pollution at every stage of the life cycle, from extraction, processing, and transport of fuels to eventual combustion. This contrasts with renewable energy technologies, for which most of the pollution and emissions occur during the manufacturing and construction phases.

> Fossil fuel sources produce CO_2 emissions and harmful air and water pollution at every stage of the life cycle, from extraction, processing and transport of fuels to eventual combustion.

In 2021, fossil fuels represented more than three quarters of the total energy supply, comprising 30% oil, 27% coal and 24% natural gas.[72] Coal is responsible for 44% of global emissions from the burning of fossil fuels, followed by oil (30%) and fossil gas (22%), and these fuels have among the highest emissions per unit of electricity generated.[73] China and the United States collectively contribute 45% of global fuel combustion emissions, followed by the EU, India, the Russian Federation and Japan.[74]

The fuels with the highest emissions from combustion in 2022 were coal, peat, and oil shale, at 15.5 gigatonnes of CO_2 equivalent, compared to 7.3 gigatonnes for fossil gas and 11.2 gigatonnes for oil.[75] The increased deployment of renewables,

FIGURE 9. Estimated Life Cycle Greenhouse Gas Emissions Intensity of Different Electricity Generation Technologies



Note: For biopower, co-firing is not included. Nuclear refers specifically to light water reactor technology (LWR). CSP refers specifically to trough and tower technology. The figure is based on an NREL study considering around 3,000 published life cycle assessment studies on utility-scale electricity generation.

Source: *NREL. See endnote 85 for this chapter.*

electric vehicles and heat pumps in 2022 prevented the further addition of an estimated 550 million tonnes of CO_2 equivalent.[76] The life cycle emissions associated with coal range from 675 to 1,689 grams of CO_2 equivalent per kWh.[77]

As offshore oil production has extended into deeper and more distant waters, the environmental risks and incidents have grown. During the 2010 Deepwater Horizon disaster off the coast of the southern United States, around 4.9 million barrels of oil were discharged into the Gulf of Mexico over the course of 87 days before the well was successfully capped.[78] This massive oil spill had devastating consequences for marine life, coastal ecosystems and the economy of the Gulf region.[79]

The combustion of fossil fuels releases massive amounts of airborne fine respirable particles[i] that are extremely hazardous to human health.[80] An estimated 1.2 million deaths were directly related to fossil fuel combustion in 2020.[81] This included fatalities from heart attacks, respiratory disorders, stroke and asthma.[82] Emissions of outdoor particulate matter are responsible for an estimated 10 million premature deaths annually.[83] In 2018, air pollution from fossil fuels was associated with health and economic costs totalling an estimated USD 2.9 trillion, or around USD 8 billion a day.[84]

Pollution and Greenhouse Gas Emissions: Renewables

Renewable energy technologies are the best option to drastically reduce greenhouse gas emissions and related air pollution (► see Figure 9).[85] Most renewables do not emit air pollutants during operations, and they contribute to improved air quality when replacing fossil fuels.[86] The operation of most renewable technologies can avoid the long-lasting soil and water pollution associated with the extraction of fossil fuels and uranium.[87]

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[i] This includes particulate with an aerodynamic diameter of 2.5 μm or less (PM2.5), in addition to sulphur dioxide, nitrogen oxides, polycyclic aromatic hydrocarbon (PAH), mercury and volatile chemicals that form ground-level ozone.

The direct impacts of renewable energy deployments depend on the location, technology, and mitigation measures in place, as well as on the approaches, standards and policies being applied. Renewables can introduce indirect pollution from raw material extraction, transport, and manufacturing, although to a lesser degree than fossil fuels.

Calculations of life cycle emissions intensity reveal that, despite the emissions generated during the production of minerals for the energy transition, and during the construction of renewable energy plants, renewables still bring large climate advantages when compared to non-renewable sources.[88]

Biodiversity

Over the past 50 years, wildlife populations have plummeted, with research suggesting that around 1 million species face extinction[i] - many in the next few decades.[89] Biodiversity loss is driven by human activities, including land-use change, climate change and pollution together with the over-exploitation of natural resources and the introduction of invasive species.[90] Preventing further biodiversity decline and restoring nature is as crucial as tackling climate change, and actions towards this aim must be interconnected.[91]

Biodiversity: Fossil Fuels and Nuclear Power

The impacts of fossil fuels and nuclear energy on biodiversity are profound and result in large part from habitat destruction, land degradation and ocean acidification (driven by increased carbon emissions).[92] Incidents such as oil spills and nuclear accidents have the potential for widespread environmental contamination, while the storage and disposal of radioactive waste present long-term risks to both aquatic and terrestrial habitats.[93] Extracting cooling water from natural environments also poses significant risks to aquatic species.[94]

The increase in CO_2 emissions associated with fossil fuels can damage plant life, degrade soil chemistry, and lessen the available food and habitat for wildlife species. Extreme weather events are affecting animal migration patterns, from the timing and routes of bird migrations to movements of African elephants.[95] Rising temperatures are pushing some plant and animal species to higher elevations, which could lead to the extinction of species that live only near mountain summits.[96] Higher temperatures are enabling insects (such as mosquitoes) to move into new areas, bringing new viruses that can infect both wildlife and humans.[97] Because of climate change, an estimated 35% of plant and animal species could become extinct in the wild by 2030.[98]

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[i] Species are at risk of extinction due to human activities, environmental changes and other factors. Common causes of species endangerment include habitat destruction, hunting and poaching, introduction of invasive species and climate change.

The extraction, processing, and transport of fossil and nuclear fuels, and the use of these fuels to produce energy, can lead to air and water contamination through the release of toxic chemicals, oil spills from tankers and pipelines, and wastewater – affecting both aquatic life and terrestrial animals. Areas that are both rich in biodiversity and have large fossil fuel reserves – such as northern South America and the western Pacific Ocean – are at particularly high risk.[99]

Biodiversity: Renewables

Renewable energy technologies offer an opportunity to minimise or eliminate the habitat destruction, land degradation and pollution associated with fossil fuels. Renewables such as wind power and various types of solar energy typically occupy smaller spatial footprints and do not entail extensive land alterations. Renewable energy technologies can be deployed strategically on previously disturbed or degraded land, working in synergy with existing land uses such as agriculture and aquaculture. In addition, integrating renewables into the built environment reduces the need to convert natural habitats into energy production areas. In some cases, such installations can provide habitats for wildlife.

The deployment of renewables can have negative impacts on biodiversity when proper spatial planning and assessment are not carried out beforehand (or when they are carried out but are not followed up with mitigation measures).[100] These impacts are specific to each technology and project and can occur across the project life cycle, from the extraction of raw materials and construction to operation and decommissioning.

If not carefully planned using existing good practices, renewable energy deployment can threaten biodiversity through habitat loss and fragmentation[i], alteration of migration routes, pollution, and changes in water quality and availability.[101] If appropriately planned and regulated, these risks and potential threats can be mitigated or avoided.[102]

> ✓ Renewable energy technologies offer the opportunity to minimise or eliminate the habitat destruction, land degradation and pollution associated with fossil fuels.

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[i] Habitat fragmentation is the division of large, contiguous habitats into smaller, isolated patches, which can cause problems for wildlife populations and the plants and animals that depend on them. Habitat fragmentation can result from human activities such as urbanisation, deforestation and other land-use changes. It can lead to a decline in the size and connectivity of habitats and can create barriers to movement and gene flow, increasing the risk of species extinction.

ECOSYSTEM INTERACTIONS BY TECHNOLOGY

The potential environmental impacts associated with renewables vary widely by technology. Insights into both the benefits and potential impacts of these technologies can be considered across the four crucial categories of: land use, water use, pollution and greenhouse gas emissions, and biodiversity. A wide range of measures exist to help mitigate or prevent potential negative impacts. Good practices and guidelines can be identified by exploring an array of government regulations, policies, standards and industry initiatives.

BIOENERGY

Bioenergy uses biomass (solid, liquid or gaseous) to produce heat, electricity, and fuels for transport and other applications (such as methane, ethanol and biodiesel).[103] **Traditional biomass** involves burning woody biomass, charcoal and agricultural residues in simple and inefficient devices for residential cooking and heating.[104] **Modern bioenergy**, the focus of this discussion, refers to the more sustainable use of biomass in high-efficiency systems.[105]

Bioenergy for heat and electricity production can rely on wastes and residues from forestry and timber processing; agricultural crop production and processing; and municipal, organic and industrial wastes.[106] Other sources can include dedicated forestry plantings and short-rotation woody crops.[107]

Liquid fuel production depends on crops such as maize, sugar cane and vegetable oils (sometimes called "conventional" or "first-generation" biofuels[i]). Other feedstock sources include perennial grasses or trees, agricultural and forest residues, waste vegetable oil and industrial bio-wastes.[108] These fuels are produced using physical, thermochemical, and biochemical technologies, following pre-treatment of the biomass feedstock.[109]

In 2020, modern bioenergy provided an estimated 5.7% of total final energy consumption and accounted for around 47% of all renewable energy use.[110] It provided around 7.6% (14.7 exajoules, EJ) of the global energy used for heating and 2.4% (1.8 EJ) of the electricity supply.[111] Biofuels provided 3.6% of transport fuels (4.1 EJ in 2021), with ethanol being the major source (2.3 EJ).[112]

Oak Ridge National Laboratory

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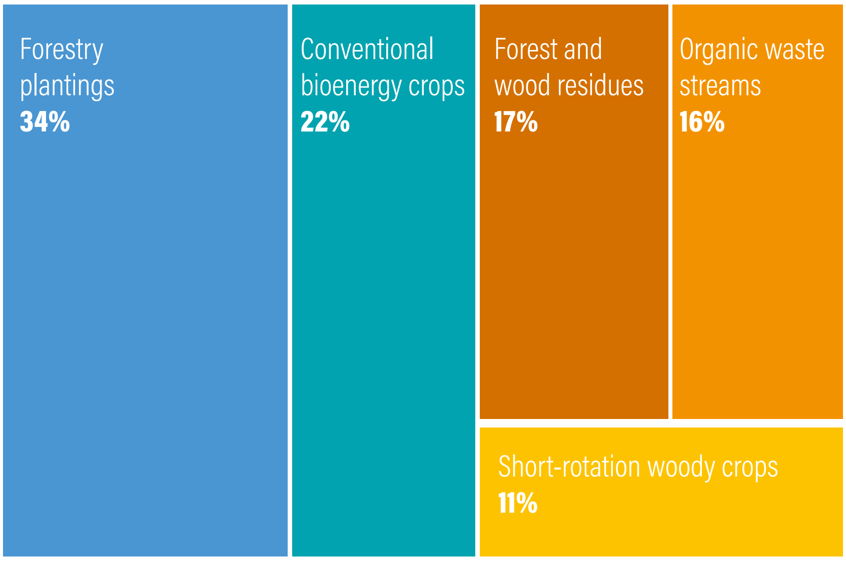
[i] The categorisation of biofuels into "first generation", "second generation", "advanced" , etc. is not favoured in this report, as there are no standard definitions and their use can lead to confusion.

FIGURE 10. Feedstock Supply for Modern Bioenergy, 2020



Source: *IEA. See endnote 114 for this chapter.*

Organic waste streams (such as crop residues) and forest and wood residues made up 33% of bioenergy supply in 2020.

The total supply of biomass for modern bioenergy use was an estimated 38 EJ in 2020.[113] Of this, around 22% (8.3 EJ) was associated with conventional annual crops for biofuels production (► see Figure 10).[114] Organic waste streams (such as crop residues) and forest and wood residues made up a further 33% of supply, and the rest came from short-rotation and forestry plantations.[115]

Bioenergy plays an important role in most scenarios targeting a low-emission energy future. It can be used to replace fossil fuels, especially in sectors where emissions are otherwise difficult to reduce (such as aviation, shipping and some industrial processes).[116] The scope for increasing the contribution of bioenergy remains uncertain and controversial, with differing estimates of the long-term potential.[i],[117] There are wide variations in life cycle analyses owing to the diverse technologies, feedstocks and locations.[118]

Regulations and requirements imposed by supporting programmes play important roles in ensuring that bioenergy production complies with stringent sustainability criteria.

Some stakeholders have called for the implementation of stringent sustainability criteria for bioenergy, related to land-use change, deforestation, pollution, greenhouse gas emissions and biodiversity.[119] National or regional policies and regulations, and requirements imposed by supporting programmes, can ensure that such criteria are met. Examples include the EU's Renewable Energy Directive, the US Renewable Fuel Standard and Brazil's RenovaBio programme.[120]

Certification bodies and other initiatives can play a key role in verifying that sustainability regulations and standards are met, with standards that parallel or go beyond regional and national legislation. For example, the Global Bioenergy Partnership (GBEP) has established 24 voluntary indicators – which cover environmental, economic and social aspects – to guide and inform national analysis, policy development and monitoring.[121] The Glasgow Declaration on Sustainable Bioenergy is an industry-led initiative to guide and support sustainability practices in woody biomass.[122] There remains a need for governments and the industry to harmonise global standards and to ensure best practice through regulations and incentives, as well as rigorous monitoring and enforcement.[123]

Land Use

Bioenergy can potentially provide benefits to local ecosystems, depending on the choice of feedstocks and on where and how they are grown. The production of biomass from agroforestry systems, degraded lands, and farmland where there is no

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[i] In some cases, unsustainable practices have been reported, with some companies accused of using whole-tree timber instead of forestry residues, underlining the importance of standards and regulations. See endnote 117 for this chapter.

direct competition with crops can increase soil quality, enhance biodiversity, reverse land degradation, and combat desertification, while minimising effects on food security (► see Box 3).[124]

Where bioenergy is produced from dedicated crops, the land requirements vary enormously depending on what crop is grown.[125] Land intensity ranges from nearly zero to levels higher than for any other energy source.[126] The estimated land-use intensity of electricity produced from biomass residues is similar to that of wind power, at 130 hectares per TWh annually (based on the power plant footprint, with no land needed for growing feedstock).[127]

For transport biofuels, a 2011 study suggests that 1 hectare of land can produce 700 litres of biodiesel from soy plants and as much as 3,600 litres from palm trees.[128] By 2050, with the increased productive and conversion efficiency of feedstock, yields could reach 900 litres per hectare for cultivated soy and 4,800 litres per hectare for cultivated palm.[129] Yields for maize, sugarcane and soybean biofuel feedstock in the United States and the EU vary widely as well (► see Table 1).[130]

Many of these crops also produce other products, such as animal feed (maize, wheat) and molasses (sugar cane), and there is a growing trend of optimising the product mix through the operation of a "biorefinery" that produces multiple products.[131] This overall product portfolio should be accounted for when considering land-use intensity.

In general, the potential environmental impacts of bioenergy crops are more important to consider than the intensity of the land use, and these impacts are determined by the feedstock type, scale of production, land type and location.[132] Large-scale feedstock production requires large land areas and may result in land conversion and degradation if sustainable agricultural practices are not followed.[133] Indirect land use could occur when bioenergy crops replace food, feed or fibre crops that are still in demand and whose cultivation therefore shifts to other land (► see section on greenhouse gas emissions).[134] Bioenergy crops produced on good-quality agricultural land can have negative impacts on food security, land degradation, water availability and biodiversity.

TABLE 1. Land-Use Intensities for Different Biofuel Feedstock Crops in the United States and the European Union

	United States ha per TWh	EU ha per TWh
Maize	23,700	22,000
Sugar cane	27,400	23,900
Soybean	29,600	47,900
Cellulose, short-rotation coppice	56,500	41,000
Cellulose, residue		10

Source: *See endnote 130 for this chapter.*

Box 3. Biogas Done Right Initiative

Through the Biogas Done Right Initiative, a group of farmers in Italy used farm-based anaerobic digestion units to produce biogas and feed electricity into the national grid. The farmers used double cropping methods to avoid reducing the volume of crops grown for food. The double crop was fed to the digesters alongside other wastes and animal manures, with the resulting gas captured and the solids returned to the fields to increase soil carbon. Long-term use of this method could increase soil organic matter. Producing biogas in this manner also could be used to generate biomethane as an alternative to fossil gas.

Source: *See endnote 124 for this chapter.*

Policy and regulatory measures can be designed to avoid deforestation and favour bioenergy feedstocks that rely on wastes, residues and crops grown on unused or underproductive land. Under the EU's Renewable Energy Directive, biofuels produced from such sources count double towards a country's renewable energy target, and producers are entitled to twice the financial support granted to crop-based biofuels.[135] The regulation also limits the extent to which crop-based biofuels can contribute to national decarbonisation targets.[136] Further measures are designed to minimise land-use change that gives rise to greenhouse gas emissions and to protect biodiversity.[137]

In Brazil, the National Agro-Ecological Zoning of Sugarcane allowed the government to promote the expansion of sugarcane production in areas that were most favourable for cultivation (in terms of the potential output) and least in need of irrigation.[138] Areas that were environmentally fragile and had high biodiversity were designated as off-limits for ethanol crops.[139] However, the regulation was revoked in 2019, which highlights the need for stable policies, effective stewardship and global sustainability standards.[140]

The Food and Agriculture Organization of the United Nations (FAO) has developed the Bioenergy and Food Security (BEFS) approach to support countries in designing and implementing sustainable bioenergy programmes, policies and strategies that promote food and energy security while advancing agricultural and rural development.[141] The BFES approach consists of tools and guidance on bioenergy policy development and implementation.[142]

There is potential to reduce the land use associated with bioenergy by using residues and wastes as feedstocks, Water demand for bioenergy varies widely depending on the crop and on rainfall levels at the growing location.

optimising crop choice, increasing productivity and co-producing feedstocks for energy and food.[143] However, the important issue is not how much land area is required, but rather the type of land being used, the impact of land-use change on carbon stocks (in vegetation and in the soil), competition with food and other important material production, forest and ecosystem integrity, and biodiversity.

Water Use

Bioenergy systems can have positive impacts on water availability and quality. For example, treating wastewater[i] to produce methane can improve water quality, allowing it to be re-used for irrigation and other purposes.[144]

For bioenergy produced from residues and wastes, the water impacts are associated with the processing and conversion of fuels.[145] Bioenergy produced from biomass crops, such as conventional biofuels from maize or sugar, could have negative impacts on water availability or quality if the crops require extensive irrigation or are planted in areas facing water stress.[146]

Water demand varies widely depending on the crop and on rainfall levels at the growing location. A study exploring the water footprint of 12 different conventional ethanol biofuel feedstocks reported a range of 238 to 1,683 litres per kWh, with the lowest footprint for sugar beet and the highest for sorghum.[147] For biodiesel feedstocks, the highest values were for jatropha (2,314 litres per kWh) and rapeseed (1,472 litres per kWh).[148] The study included water use during irrigation, rainwater loss during evaporation and water pollution during production. In the EU, the estimated consumptive water footprint for first-generation ethanol is 220 litres per kWh and for biodiesel is 495 litres per kWh.[149]

Many feedstocks for biofuel production do not require irrigation. In Brazil, only 1% of the sugarcane crop is irrigated.[150] Wastewater from sugar and ethanol production (vinasse) is used when crops are too dry and provides nutrients for the crop. In the United States, irrigation requirements for maize grown for ethanol production vary widely among states depending on rainfall levels – from 5 litres of water per litre of ethanol in Ohio to 2,138 litres in California.[151]

The impact of biofuels on water demand can be reduced by growing feedstocks in areas with ample rainfall, choosing feedstocks that require minimal water, and promoting residue and waste-based feedstocks.[152] Using wastewater to irrigate and fertilise energy crops reduces the demand for "clean" water.[153] Regulations also can constrain water use. For example, authorities in the Brazilian state of São Paulo, which has the country's largest concentration of ethanol and sugar mills, established a water use limit in the sugarcane industry of 1 m^3 per million grams of cane (reduced to 0.7 m^3 in areas suffering from water scarcity) as part of the Agro-Environmental Zoning for Sugar Alcohol Sector.[154]

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[i] For example, sewage and industrial effluents, and animal manures and waste products.

Pollution and Greenhouse Gas Emissions

Bioenergy production generates greenhouse gas emissions at the point of use. However, biomass-based systems form part of a natural cycle of growth and decomposition, operating within the carbon cycle.[155] In contrast, the use of fossil fuels involves a transfer of carbon from geological reservoirs to the atmosphere, thereby increasing atmospheric CO_2 levels.

Accurate comparisons among bioenergy technologies can be made only by considering overall net emissions as well as both direct and indirect effects. Such calculations are highly complex, with specific issues that need to be considered for each combination of feedstocks, production and processing methods, and end uses.[156]

Documented case studies show that the production and use of biomass can provide climate and other benefits, reducing greenhouse gas emissions by replacing the use of fossil fuels.[157] Emission reductions can be achieved by using crop residues that would otherwise be burned in the field, collecting and using methane that would otherwise be emitted from landfill sites, and collecting farm wastes and organic liquid effluents.[158] Emissions also can be reduced through the collection and use of forestry by-products as part of a sustainable forestry management plan that aims to reduce risks of uncontrolled fires and thus preserve forest carbon stocks.[159] Studies have found that increasing plant diversity in bioenergy crops can augment the amount of carbon stored in the soil and reduce greenhouse gas emissions, without compromising crop productivity.[160]

> ✓ Treating wastewater to produce methane also improves water quality, allowing it to be re-used for irrigation and other purposes.

Reducing **supply chain emissions** – which are generated when fossil fuels are used to produce, harvest, convert, transport and use bioenergy – can further these benefits.[161] In addition, emissions of other greenhouse gases may occur and must be taken into account; these include nitrous oxide (N_2O) and methane (CH_4) from land-use changes, agricultural management, and fertiliser production and application, as well as from biomass storage and biogas processing.[162] As more renewable energy is used directly in the bioenergy supply chain, related emissions will decline as well.[163]

Supply chain emissions are well understood and can be calculated with some certainty using life cycle assessment tools. LCA reveals that, compared to fossil fuels, many bioenergy pathways can have much lower supply chain emissions.[164] The European Commission provides default emission values for a wide range of bioenergy value chains.[165] While the numbers vary for different supply chains, emissions associated with bioenergy can be up to 80-85% lower than the fossil fuel equivalent.[166] In some cases, anaerobic digestion of wastes can lead to a net reduction in greenhouse gas emissions for each unit of biomass.[167]

Bioenergy may contribute fewer benefits if its production and use leads to reductions in the carbon stocks of soils or vegetation or negatively affects the carbon cycle. Such **"biogenic emissions"** are more difficult to understand and quantify, and there is less agreement about the consequences.[168] The main greenhouse gas concerns are related to land-use change[i] and the use of forestry products.[169]

Pressure to produce biomass for energy or other purposes can lead to the expansion of croplands into primary forests and other areas that have high carbon stocks, resulting in what is termed **direct land-use change**.[170] Such incursion can lead to reductions in the carbon stock, habitat loss, and the degradation of soils and water bodies.[171] If carbon-rich land is converted to produce bioenergy feedstocks, this would lead to a net increase in greenhouse gas emissions, despite the emission savings obtained from displacing fossil fuel.[172]

There is also concern about **indirect land-use change**. If producing bioenergy or other biomass-based products requires the conversion of additional land to cropland to maintain lost production, this could promote deforestation and other land-use change, in turn leading to increased greenhouse gas emissions and the loss of carbon stocks.[173] Estimating such indirect change is a challenge given the complex interactions within the global agricultural and land-use system. Estimates rely on complex modelling, with differing answers that depend on the many assumptions made.[174]

Early research on indirect land-use change suggested potentially significant impacts that could diminish the carbon benefits of crop-based biofuels; however, subsequent analysis has revealed a smaller range of likely impacts.[175] Studies confirm the potential importance of indirect land-use change in cases where crop cultivation (such as for palm oil production) provokes the expansion of agriculture into primary forest areas, exposing high carbon-containing peat soils, whereas the impacts are much lower for other crops, such as maize and cereals.[176] Even so, different modelling studies produce wide-ranging emission estimates.[177]

Another issue sparking concern is the use of forest feedstocks for bioenergy. With regard to greenhouse gas emissions, the main issues relate to the impacts of using forest-based materials on forest carbon stocks, as well as the timing of these impacts, since for some forest materials the biogenic carbon cycle can be long (forest rotations are lengthy, and biomass decay can be relatively slow).[178] The carbon impacts of harvesting and using forest biomass depend on many factors – such as the climate, growth rates and current use patterns – and need to be assessed at a local level and compared with a realistic counterfactual scenario.[179] Such analysis can establish the relative magnitude and timing of positive or negative impacts. Although the modelling of these impacts is possible, it is difficult to ensure that the modelling is based on actual forestry practice and that a proper counterfactual is used.[180]

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[i] That is, changing land use to accommodate crops grown for non-food purposes.

Sidebar 2. Comparing Agroforestry Systems to Open Cropland and Grassland in Germany

In rural, decentralised areas of many temperate regions, open croplands are managed intensely for higher productivity but have associated negative environmental effects. The rising demand for fuelwood has led to increased interest in agroforestry systems. However, comprehensive research on agroforestry's potential to enhance ecosystem functions is lacking. Recent research in croplands in the German regions of Thuringia, Lower Saxony, and Brandenburg, and in grasslands in Lower Saxony, aimed to study the ecosystem benefits and functions of alley-cropping agroforestry.

The project compared the multi-functionality of alley-cropping agroforestry using short-rotation trees to conventional open croplands and grasslands across different soil types and climatic conditions. In the study, open croplands were managed with rotating crop monocultures and received standard applications of fertilisers and agrochemicals, whereas open grasslands were permanent grassy areas without trees. The study used multiple indicators of different ecosystem functions collected over a four-year period at five sites.

In each study site, the alley-cropping agroforestry comprised 12-metre-wide rows of trees alternating with 48-metre-wide rows of crops or grassland. The agroforestry crop rows and open croplands were managed conventionally, including annual cultivation and the application of recommended mineral fertilisers and agrochemicals. The tree rows were not fertilised and were harvested after four to seven years for bioenergy purposes, thus removing the woody biomass from the field. The researchers studied carbon sequestration and soil greenhouse gas reduction, and also measured the presence of phytopathogens.

The study found that converting croplands and grasslands to alley-cropping agroforestry did not negatively impact crop or grass yields. A slight reduction in crop yield near the tree rows was offset by increased yield in the centre of the crop row. The fibre and protein content of grassland agroforestry remained unchanged, while the crop quality in cropland agroforestry improved partially, with higher wheat, crude starch, and canola crude protein contents, as well as greater canola 1,000-grain weight compared to open cropland.

The trees contributed greatly to increased carbon sequestration in both the cropland and grassland agroforestry. Agroforestry improved the soil habitat for biological activity, reduced the wind speed and erosion risk in cropland agroforestry, and improved the gross rates of nitrous oxide uptake in the soil. Other ecosystem functions – such as soil nutrient cycling, soil greenhouse gas abatement and water regulation – did not change significantly. With no reduction in the measured ecosystem functions, agroforestry improved carbon sequestration, soil habitat, and erosion resistance functions in croplands, and carbon sequestration in grasslands.

Source: *See endnote 188 for this chapter.*

Greenhouse Gas Mitigation Measures

Supply chain emissions can be reduced by minimising the use of fossil fuels in the bioenergy supply chain. This can be done, for example, by using biomass residues for feedstock drying or for heat and power generation; by processing feedstocks close to the source and using efficient transport; and by co-producing other energy and non-energy products such as animal feed.[181]

Policy mechanisms designed to promote bioenergy often set minimum conditions for greenhouse gas savings or incentivise such savings in other ways. EU regulations specify that, compared to fossil fuels, biomass used for heat or electricity production must lead to at least a 70% reduction in greenhouse gas emissions (to be increased to 80% in 2026), and transport biofuels must lead to a 65% reduction in emissions.[182] The US Renewable Fuel Standard provides higher levels of support for low greenhouse gas options.[183] Both the California Low Carbon Fuel Standard and Brazil's RenovaBio programme provide incentives for biofuel use based on assumed greenhouse gas savings.[184]

Great potential also exists to produce biomass for energy without causing direct or indirect land-use change.[185] The use of post-consumer organic residues or agricultural/forestry by-products as feedstocks does not require land-use change or result in any reduction in soil carbon stocks.[186] Alternatively, feedstocks grown on existing agricultural land can achieve higher yields through improved cultivation practices, and energy crops can be produced on suitable developed land that has become degraded or marginal and is unfit for food or feed production.[187] Crop rotations and intercropping systems, including wide-ranging agroforestry systems (► see Sidebar 2) can provide feedstocks along with food.[188] For example, the oil-yielding plant *Brassica carinata* can be cultivated as a winter crop, complementing conventional food crops that are grown at other times of the year.[189]

Wider efforts to reduce and eradicate deforestation will help avoid land-use change emissions associated with products, including bioenergy. Bioenergy governance regimes also can take specific measures to exclude the use of materials associated with direct land-use emissions along with negative impacts on biodiversity or food security from support schemes. For example, the EU Renewable Energy Directive (RED II) excludes support for bioenergy produced from raw materials grown on land that has carbon stocks (or land with high biodiversity value).[190] This includes wetlands and continuously forested areas. Other support schemes, such as California's Low Carbon Fuel Standard, factor in modelled estimates of indirect land-use emissions when calculating the greenhouse gas savings.[191]

Regulations often require that forestry feedstocks are produced from certified forests that meet sustainable forestry requirements (thereby ensuring that the feedstocks have been legally sourced) and comply with local, national and applicable international


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Crop rotations and intercropping systems, including wide-ranging agroforestry systems, provide bioenergy feedstocks along with food.

laws and regulations relating to forest management (ensuring that forest productivity is maintained).[192] In addition, regulations – such as the EU's revised Renewable Energy Directive – seek to ensure that forestry feedstocks come only from forests in which stocks are being preserved and that criteria related to land use, land-use change and forestry are achieved.[193]

Pollution

Bioenergy production can potentially have positive or negative impacts on air, water and soil quality. The risks of negative impacts can be minimised through the adoption of good practices, reinforced by regulations that are strictly enforced. Potential benefits to air, water and soil quality from the production and use of biomass feedstocks include the following:

- Air quality improvements can occur when biomass is used as feedstock in efficient equipment equipped with flue gas cleaning systems, rather than being burned under uncontrolled conditions. In India, crop residue burning is a major cause of air pollution in many cities, and providing alternative options is an important driver for the country's bioenergy programme.[194]

- Using waste materials as energy can provide income streams that encourage good waste management practices, reducing environmental impacts (so long as projects are carefully planned and operated, and monitored).[195]

- Treating wastewater (such as sewage and industrial effluent) and converting animal manures and waste products into methane using anaerobic digestion can reduce fugitive methane emissions.[196]

If not carefully managed, the combustion of biomass can result in air pollution, including particulate matter, nitrogen oxides, carbon monoxide and other hazardous air pollutants.[197] The use of fertilisers or pesticides when growing energy crops can lead to pollution of soils and water bodies.[198] In addition, if not properly treated the wastewater from bioenergy refineries could pollute groundwater.[199]

Pollution Mitigation Measures

Stringent local air quality regulations and their strict enforcement can ensure that bioenergy does not adversely affect air quality. The best boilers and stoves available meet very stringent air quality standards by controlling combustion conditions and using pollution control systems.[200] In the EU, new wood boilers and stoves must meet Ecodesign standards, which set strict emission limits.[201] An integrated approach to waste management can ensure that the use of waste for energy is appropriate, and stringent air and water quality regulations, with regular monitoring and enforcement, can ensure that operations avoid negative impacts on air and water quality.[202]

Crop residue removal for energy purposes needs to be constrained to limits that maintain soil carbon and do not compete with use of residues as feed for livestock.[203] Certification procedures can include measures to ensure that harvesting is restricted to acceptable levels to conserve soil quality, with monitoring to ensure that these measures are effective.[204] Strict national and local regulations on the use of pesticides and fertilisers and on discharges of effluents (applied generally in agriculture) can be enforced to ensure that bioenergy crop production does not contribute to water pollution.[205]

Biodiversity

The impact of bioenergy on biodiversity varies depending on the feedstock type, the location and scale of production, the reference ecosystem, and the management practices used. All these criteria must be considered to gain a clearer picture of the impacts.[206]

Land-use changes associated with the cultivation of bioenergy feedstocks have the potential to result in biodiversity losses. The choice of feedstock grown can be made to avoid biodiversity losses related to monoculture plantations and invasive species, and there is a clear consensus on the importance of avoiding the use of virgin forest materials.[207] Bioenergy can promote forestry and the growth of perennial energy crops that are more biodiverse than annual crops such as cereals, and can have positive effects when planted on under-used or degraded land.[208]

Biofuel crop cultivation on damaged or unused land, and the replacement of annual crops with more resilient perennial varieties, have proven especially beneficial for multifunctional agriculture and ecosystems.[209] Growing bioenergy crops on degraded and marginal lands[i] makes use of deserted or abandoned lands or lands that have lost their productivity following intensive agricultural or industrial use.[210] Such re-use can help mitigate or avoid potential

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[i] Marginal land is land with low agricultural productivity and economic potential. The term is often used interchangeably with terms such as degraded land, wastelands and abandoned land.

Biofuel crop cultivation on damaged or unused land, and the replacement of annual crops with more resilient perennial varieties, have proven beneficial for multifunctional agriculture and ecosystems.

land-use competition and conflict.[211] Another option to use and improve degraded land is to cultivate fast-growing trees (short-rotation woody crops) on plantations, which can provide economic value to the wood-energy value chain.[212]

The use of invasive species as bioenergy feedstocks can help address the spread of this vegetation. In South Africa, bioenergy use is being promoted to encourage harvesting of invasive species and to reduce water loss, and potentially as a source of sustainable aviation fuel.[213] By clearing invasive alien plants, native ecosystems are more able to thrive.

Inappropriate production and harvesting of biomass, however, can lead to a loss of biodiversity or to the proliferation of invasive species.[214] A meta-analysis of eight[i] of the most-studied bioenergy crops found that feedstocks derived from oils, sugars and starches tend to have greater impacts than those derived from lignocellulose, woody crops, or residues.[215] Bioenergy feedstocks derived from woody crops or residues result in around one-fifth the reductions in species abundance and diversity.[216]

Of particular concern is the impact on biodiversity of using forestry residues, especially when linked to forestry practices that involve "clear-cut" harvesting.[217] A recent EU report highlights the biodiversity impact of removing different types of post-harvesting residues from the forest and recommends that energy use should concentrate on secondary residues produced in sawmills and wood processing sites.[218] Regulations can restrict biomass production and harvesting in biodiverse areas. For example, the EU RED II excludes support for bioenergy produced from raw materials produced on land with high biodiversity value, including primary forest and other biodiverse wooded land and biodiverse grassland.[219]

The measures highlighted above, aimed at regulating and reducing land use and land-use change, pollution, and greenhouse gas emissions, all contribute to mitigating impacts on biodiversity (► see also the solutions table at the end of this chapter).

GEOTHERMAL ENERGY

Geothermal energy technologies harness the high temperatures found beneath the Earth's surface for heating and electricity generation. With documented use spanning at least 2,000 years, direct-use of geothermal energy for thermal applications is most prominent in space heating and for swimming pools and baths, but also for crop cultivation (via greenhouses and covered ground heating), aquaculture, agricultural drying, snow melting and industrial processes.[220] Due to the high cost of transporting hydrothermal energy long distances – such as long-distance coupling with district heating networks – it is common to co-locate end-use demand and geothermal heat production. Examples include thermal baths and greenhouses in Japan and Iceland.[221]

The global geothermal heat capacity was an estimated 35 gigawatts-thermal in 2022.[222] The installed geothermal power capacity totalled an estimated 14.6 GW (up from 14.5 GW in 2021).[223] For electricity generation, 0.2 GW of new geothermal capacity was added in 2022, one-third less than in 2021.[224] Geothermal energy generated 101 TWh of electricity and an estimated 155 TWh of direct useful thermal energy in 2022.[225] To achieve the IEA's pathway towards net zero greenhouse gas emissions, total electricity generation from geothermal sources


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[i] Eucalyptus, jatropha, oil palm, poplar, switchgrass, soy, sugar cane and pine.


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would need to increase to an estimated 306 TWh by 2030 and 862 TWh by 2050 (requiring a total installed capacity of 48 GW and 129 GW, respectively).[226]

In 2021, the International Geothermal Association assumed oversight of the Geothermal Sustainability Assessment Protocol (GSAP), adapted from the 2010 Hydropower Sustainability Assessment Protocol.[227] The GSAP provides a structured approach to assessing geothermal energy projects and covers diverse aspects, including environmental, social, economic and technical considerations. It provides guidance on potential impacts to be assessed prior to project development, as well as examples of mitigation measures.

✓ Most geothermal power plants built in recent years are closed-loop binary-cycle units that do not discharge geothermal fluid on the surface or into freshwater aquifers.

Land Use

Geothermal land-use requirements are highly site-specific due to varying plant designs that depend on local characteristics (temperature, fluids, gas content, etc.).[228] Geothermal power plants typically require relatively small land areas compared to many other types of power generation facilities, including other renewables (► see Figure 6).[229] One analysis of 26 power plants in 18 countries estimates the median land-use intensity of geothermal power at 45 hectares per TWh (0.45 square metres, m^2, per megawatt-hour) annually.[230]

During construction, integrated management plans can ensure that land disturbance and waste generation activities will be managed so that later rehabilitation activities can be undertaken efficiently and effectively. This can include stockpiling of topsoil, seed collection, sensitive siting of work areas, and appropriate storage and disposal of cuttings and discharge from drilling.[231]

The injection of fluid[i] into wells at geothermal sites can induce seismicity and subsidence.[232] Fluid injection is used in Enhanced Geothermal Systems (EGS)[ii] to increase permeability and flow in the deep hot rock formations, enabling the use of geothermal energy outside areas of relatively high

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[i] For example, for environmental disposal, maintaining of pressure and fluid in the aquifer/bedrock, and well stimulation by hydraulic pressure to enhance yield of existing or new wells.

[ii] EGS, also known as Engineered Geothermal Systems or "Hot Dry Rock" geothermal systems, are a type of geothermal energy technology designed to harness heat from deep within the Earth's crust, where temperatures are much higher than at the Earth's surface. EGS technology aims to create artificial reservoirs of geothermal heat by stimulating or enhancing the flow of hot fluids through underground rock formations that may not naturally contain sufficient permeability or fluid flow.

Geothermal land-use requirements are highly site-specific due to varying plant designs that depend on local characteristics.

hydro-thermal activity. This process shears or fractures the sub-surface rock, which can induce more significant seismic activity and requires operations to be halted.[233] The GSAP suggests establishing monitoring networks for seismic measurements, as well as risk assessment plans and procedures to evaluate and address any inconvenience or damage resulting from induced seismicity and subsidence.[234]

Water Use

Geothermal facilities use water for drilling, cooling, and steam production, with the overall footprint dependent on factors such as plant size, working temperature, cooling technology (wet versus dry) and fluid (geothermal water).[235] Cooling technology is the most significant factor: wet cooling has the highest water demand, whereas air-cooled binary facilities use little to no water[i].[236]

One study found that water consumption for geothermal power plants in the United States ranged from 0 to 5.3 litres per kWh.[237] Other estimates indicate up to 15 litres per kWh depending on the plant technology.[238] In another study, the consumptive water footprint of geothermal globally ranges from an estimated 0.03 to 2.7 litres per kWh.[239] These water consumption profiles are comparable to the range for fossil and nuclear power plants, which typically consume water for cooling purposes at a rate between 0.01 litres and less than 10 litres per kWh.[240]

Some geothermal technologies can reduce water consumption, such as closed-loop systems that condense and recirculate water. In some cases, it is possible to reinject the water into the geothermal reservoir. However, geothermal plants can have a negative impact on water resources if the fluids are not properly processed and disposed of after use. In addition, if they are discharged directly into water bodies, hot fluids can increase the water temperature as well as concentrations of minerals such as arsenic, sulphide and mercury.[241] Most geothermal power plants built in recent years are closed-loop binary-cycle units that do not discharge geothermal fluid on the surface or into freshwater aquifers.[242]

Pollution and Greenhouse Gas Emissions

Geothermal energy facilities has been shown to emit substantially fewer carbon emissions than fossil fuel power plants in many regions around the world.[243] Emissions from geothermal energy are lowest in closed-loop systems, as gases removed from the well are injected back into the ground.[244] In the United States, geothermal power plants reportedly emit around 99% less CO_2 and 97% fewer acid rain-inducing sulphur compounds than fossil fuel power plants.[245] A global estimate in 2018 suggested that modern geothermal power technology emits over 90% less CO_2 equivalent per kWh on average than modern fossil-fuelled equivalents.[246]

Even in the few regions where geothermal energy is found to have comparable emissions to fossil fuel energy sources (such as some plants in Türkiye), emissions per unit of energy tend to decline over time. This is suspected to occur because gas concentrations in geothermal reservoirs drop with the re-injection of de-gassed geothermal fluid, because of dilution from the natural inflow of make-up fluid with lower gas concentration into the reservoir, or because the plant operations exceed the natural rate of recharge of gas into the sub-surface reservoir.[247]

Unlike closed-loop systems, open-loop geothermal systems can cause substantial air pollution through the discharge into the geothermal steam of gases such as CO_2, hydrogen sulphide, and traces of methane, mercury and ammonia.[248] A study in New Zealand showed that geothermal development in Waikito River released arsenic into the water and soil that had negative impacts on plants and fish.[249] These impacts also may extend to human health.[250]

Air quality management measures involve predictive modelling, mitigation plans and ongoing monitoring programmes.[251] Water quality management includes hydrological studies, addressing issues during the construction phase (e.g., oil bunding, sediment traps), long-term design features (discharge, re-injection, vegetation, soil management) and pollutant management (sewage, waste, contaminated sites), along with monitoring programmes.[252]

Biodiversity

The construction and operation of geothermal plants could have negative impacts on habitats and contribute to wildlife mortality.[253] Although research is limited, one study found that the construction and operation of Kenya's Olkaria geothermal power plant led to a decline in the species richness of birds due to higher levels of hydrogen sulphide pollution, noise pollution, habitat modification and vegetation clearance.[254] As with land impacts, the GSAP calls for sensitive site selection that prioritises opportunities for multiple use benefits and avoids disturbing unique landscapes and protected areas.[255]

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[i] However, air cooling lowers efficiency and increases the cost of energy production.

HYDROPOWER

Hydropower facilities harness kinetic energy from falling water to produce electricity. Hydropower is the largest and oldest[i] source of renewable energy used for electricity generation, with 1,220 GW of capacity in operation at the end of 2022.[256] Generation increased 5% in 2022 to reach 4,429 TWh, with hydropower accounting for 15.1% of total electricity generation.[257]

Nearly 40% of existing hydropower installations are at least 40 years old, and they will require refurbishment and modernisation in the coming years.[258] The main challenge for further deployment of the technology is the limited availability of sufficiently large and economically viable locations.[259] Moreover, climate change could disrupt hydropower operation and output, with one study finding that by 2050, 61% of dams will be in basins with high or extreme risk of droughts and floods.[260] These risks may already be materialising, as persistent droughts appear to be constraining the average capacity factor[ii].[261]

In 2021, the Hydropower Sustainability Council adopted the Hydropower Sustainability Standard, which evaluates the environmental, social and governance performance of projects based on a rating system across the project life cycle (i.e., preparation, implementation and operation).[262] The Standard covers 12 topics, including water quality, biodiversity, Indigenous Peoples, and environmental and social assessment (such as land disturbance and rehabilitation).[263] In March 2023, Pamir Energy's Sebzor hydropower project in Tajikistan became the world's first project to be certified using the Hydropower Sustainability Standard (► **see Energy Justice chapter**). In 2023, the Hydropower Sustainability (HS) Alliance became the independent and multi-stakeholder standard-setting body that oversees the HS Certification System and manages the implementation of the HS Standard.[264]

Land Use

Owing to the massive coverage of flooded areas, hydropower accounts for 80% of the land used for electricity generation worldwide.[265] A 2022 study based on more than 900 hydropower dams in 80 countries calculated a median land-use intensity of 650 hectares per TWh annually, noting significant variance.[266] The study found that the land footprint of hydropower per unit of output exceeded the median direct land footprint of fossil gas (at 410 hectares per TWh annually) but was below that of coal (at 1,000 hectares per TWh annually).[267]

The construction of large reservoirs has been known to stimulate seismic activity.[268] For example, the 2013 Badong earthquake in China was deemed to be linked to high pore pressure caused by water infiltration from the reservoir of the Three Gorges Dam.[269]

Land use and other impacts associated with dams are not necessarily attributable solely to electricity generation. Of the estimated 58,000 dams registered worldwide as of 2020, 6,100


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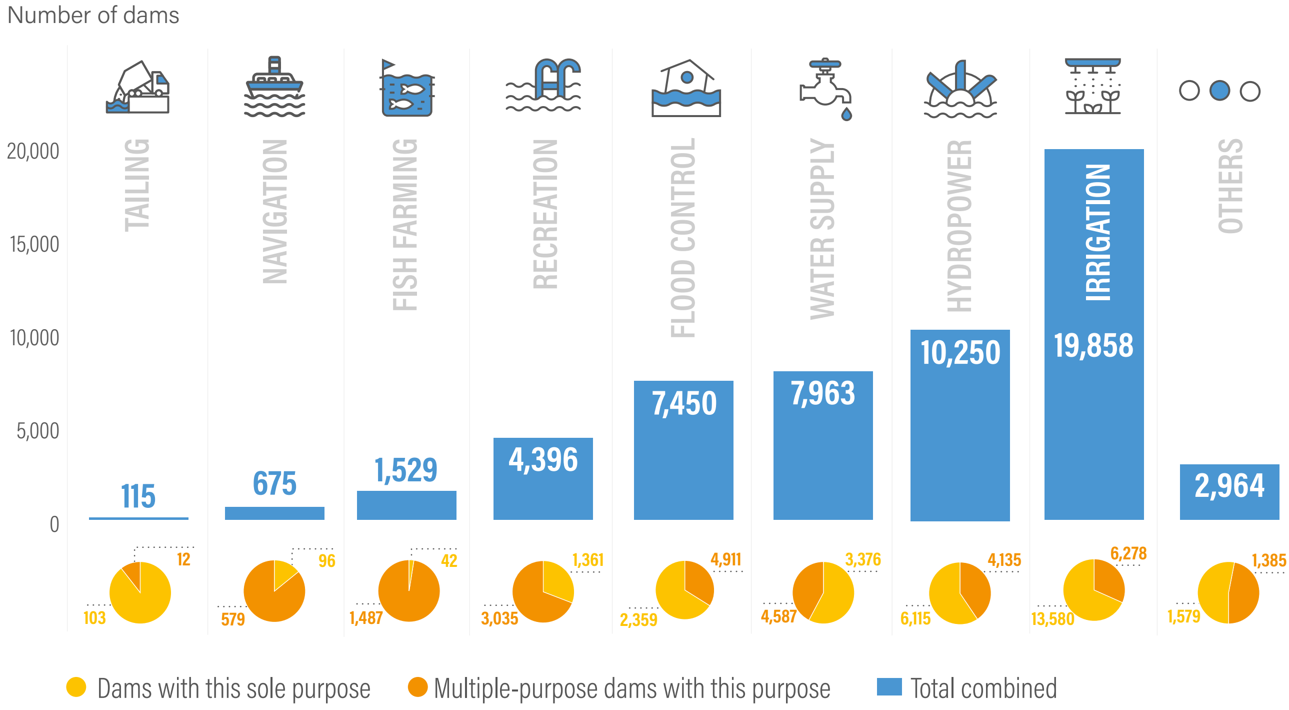
[i] The first commercial plant entered into operation in 1882. See endnote 256 for this chapter.
[ii] The actual electricity output generated by a facility relative to its maximum potential output in a given period of time.

FIGURE 11. Uses of Registered Large Dams, 2020



Source: *ICOLD. See endnote 270 for this chapter.*

were exclusively used for hydropower, whereas 4,135 were multi-purpose (► see Figure 11).[270] Hydropower dams can serve as flood control infrastructure, protecting downstream areas from flooding and potential land damage. Dams also can create opportunities for tourism, recreation, irrigation, drought management and fishing.[271]

Hydropower can be harnessed through technological options requiring low land use, such as run-of-river plants.[272] Small reservoirs often can be integrated into river systems, greatly reducing the land requirements for hydropower facilities.[273] Run-of-river plants represent around 4% of the global hydropower capacity.[274] Although many such plants are small, the capacity of some run-of-river plants rivals that of hydropower dams with reservoirs. Such plants generally have little to no storage, which reduces land requirements but results in greater variability in power generation because of seasonal fluctuations in river flow.[275]

Water Use

Estimates of the water footprint of hydropower dams with reservoirs vary. One meta-study found that the consumptive water footprint ranged from 0.04 to 209 litres per kWh (based on different methodologies and factors).[276] Another study estimated an enormous range of between 1.08 and 3,060 litres per kWh, accounting for evapotranspiration but not for multiple uses (all uses need to be considered to calculate an accurate estimate of the water footprint of hydropower plants).[277] In Europe, water footprint estimates range from 1.8 to 33 litres per kWh.[278]

Most water loss associated with hydropower occurs in the form of evapotranspiration from large dam reservoirs. The rate of this loss depends on factors such as the climate (tropical versus temperate), weather and reservoir size.[279] Evapotranspiration losses from US reservoirs average an estimated 17 litres per kWh.[280] Most methodologies attribute all evaporation to hydropower, thereby excluding other uses such as irrigation and water supply.

The water footprint of run-of-river hydropower systems is negligible because they do not have a reservoir.[281] In the EU, the average consumptive water footprint of run-of-river systems is an estimated 0.004 litres per kWh.[282]

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Hydropower dams can also serve as flood control infrastructure and create opportunities for irrigation, drought management and tourism.

Sidebar 3. Micro Hydropower for Electrifying Off-grid Areas in Mindanao, Philippines

The Mindanao island group in the southern Philippines is home to more than 26 million people and suffers from high poverty rates. Although the region has 8 major river basins and 33 major river systems as well as tributaries, around 1.7 million households still lack access to electricity. In 2019, coal accounted for more than 68% of the gross electricity production, while only 20.9% was from hydropower. Deforestation is also a significant problem, with the primary growth forest cover shrinking from 70% in the 1900s, to 23% in 1988, to 6% in 2011. Deforestation results in flash floods and landslides that deposit large amounts of sediment in rivers, even changing their course, with direct impacts on hydropower generation.

To tackle the issues of energy access and deforestation in Mindanao, the local renewable energy association Yamog has promoted an integrated solution featuring micro-hydropower and watershed management. In addition to installing micro-hydro plants, Yamog works with local communities to raise awareness and engage people in watershed management activities to ensure a continuous supply of water from the watershed for both electricity generation and conservation of the environment.

For watershed management, Yamog performs an inventory of all existing natural resources in the area to create a baseline. This is done before the micro-hydro project is installed, helping Yamog understand how best to align the watershed management and the micro-hydro construction for optimal benefit. The local community is involved in every step to raise awareness and create a sense of project ownership. Workshops are held on watershed management and forest rehabilitation, including providing tree saplings for afforestation and encouraging the community to maintain a nursery for continuous supply of the saplings.

To ensure the long-term viability of these activities, Yamog engages with local governments – such as the Barangay Local Government Unit and the Tribal Council – to gather support for each project. Yamog also encourages the energy users association to dedicate a small portion of its operations and maintenance fund to watershed management. This innovative effort to combine micro-hydro construction with watershed management is a good example of looking at energy supply from an integrated perspective. A key success factor was community ownership, which helps to ensure continuity of the project over the long term.

Source: *See endnote 298 for this chapter.*

Technological and design choices can help reduce water use. For hydropower plants with reservoirs, optimising operational efficiency and co-ordination can help reduce water loss, as can matching generation to demand and adjusting water release strategies. Hydropower facilities can provide downstream benefits. For example, reservoirs can help mitigate the effects of drought by storing water during wet periods and releasing it during dry spells.[283] This can stabilise water availability, such as for agricultural and municipal needs.[284]

Alternatives to traditional reservoirs can be considered, such as underground pumped storage or off-stream water storage, which can reduce water loss while providing flexibility in electricity generation.[285] Low-impact run-of-river systems can be prioritised where applicable.

Pollution and Greenhouse Gas Emissions

Large-scale hydropower plants can provide the kind of stable and reliable baseload power that is considered essential for meeting electricity demand without relying on fossil fuels. Small and micro-hydropower systems deployed in remote or off-grid locations can reduce the reliance on diesel generators and other greenhouse gas-emitting energy sources.[286] Nonetheless, hydroelectric dams can be sources of greenhouse gas emissions and pollution during the construction process (including the manufacture and transport of materials, such as concrete and steel), operation and decommissioning.

The creation of reservoirs can be a source of greenhouse gas emissions, released when the carbon and other organic matter in the flooded land decomposes.[287] These emissions decline over time as the level of biomass decreases. In one study, emissions from a hydropower facility that flooded a boreal forest decreased sharply from the first to the third year, leading to levels well below those of fossil gas power plants.[288]

Many factors impact the life cycle emissions from hydropower facilities, including the type and size of the power plant and the nature of the land that is flooded.[289] Estimates of the quantities of emissions released also vary depending on the methodology used to measure them.[290] Average life cycle emission estimates for all types of hydropower facilities range from 0.57 to 75 grams of CO_2 equivalent per kWh.[291]

Hydropower reservoirs may be associated with mercury pollution, depending on the age and size of the plant and on the watershed characteristics.[292] Clearing vegetation before flooding an area can potentially reduce these risks.[293] However, additional research and development of best practice guidelines are needed to reduce methane emissions and mercury water pollution from hydropower dams.[294]

Biodiversity

Hydropower dams impact freshwater sources and surrounding biodiversity mainly through changes in sediment flow and hydromorphology, as well as through the loss of habitat and range connectivity for wildlife.[295] Water quality can decline due to changes in sediment loads and nutrient cycles.[296] A small fraction of the world's hydropower projects contribute an outsized share of the impacts on terrestrial and aquatic biodiversity.[297]

Careful selection of reservoir locations for hydropower projects and the comprehensive evaluation of their impact on both terrestrial and aquatic biodiversity can mitigate negative effects. By incorporating local environmental conditions and species richness into the assessments of these projects, associated dams and reservoirs can be more strategically placed to reduce the harmful impacts on biodiversity (► see Sidebar 3).[298]

Changes in water flow have been associated with negative effects on individual species of fish, insects, invertebrates and plants.[299] Diadromous fish species (fish that can transition between fresh and salt water), such as salmon, face obstacles while migrating to spawning grounds upstream.[300] Diversity within a single species can be influenced by the development of distinct genetic variations that occur in specific locations both upstream and downstream of hydropower installations.[301] Ecosystem characteristics, such as species richness and river location, also are important considerations.[302]

During the design of dams, steps can be taken to protect migratory fish. These measures include using special structures such as curved bars to deter fish from turbine blades, using gentle electric shocks to guide fish safely, and creating fish-friendly pathways such as ladders, elevators and passes. These efforts help fish safely navigate around dams and continue their upstream journeys.[303]

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> During the design of dams, steps can be taken to protect migratory fish.

In certain cases, the creation of reservoirs behind hydropower dams can lead to the formation of wetland habitats and result in increases in wildlife, as occurred with the endangered giant otter in Brazil.[304] In Germany, the Kellerwald-Edersee National Park was established around four hydropower reservoirs in 2004 and became part of a World Heritage Site of European beech forests in 2011.[305]

Maximising the efficiency of existing hydropower plants can help lower resource footprints. Modernising hydropower plants to be more efficient can be a cost-effective way to generate more electricity from the same amount of water and land. Studies have found that retrofitting old dams with newer equipment can improve energy efficiency 4-8% and increase generation 10-30%, while being less invasive for biodiversity.[306] According to one study, such measures could provide up to a 9% increase in the global hydropower capacity, with the added benefit of avoiding the infrastructure and ecosystem impacts of new dams.[307]

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Since 2000, 36 dams with a combined installed hydropower capacity of more than 500 MW have been retrofitted in the United States.[308] In the Amazon River Basin, retrofitting and upgrading dams would result in an additional 1.6 GW of power capacity.[309] A related option is to retrofit dams that are used for other purposes (irrigation, flood control or water supply) by adding hydropower generators. This would require no additional land or water use and would avoid the harmful effects from new dams.

> Modernising hydropower plants to be more efficient is an effective way to generate more electricity from the same amount of land and water.

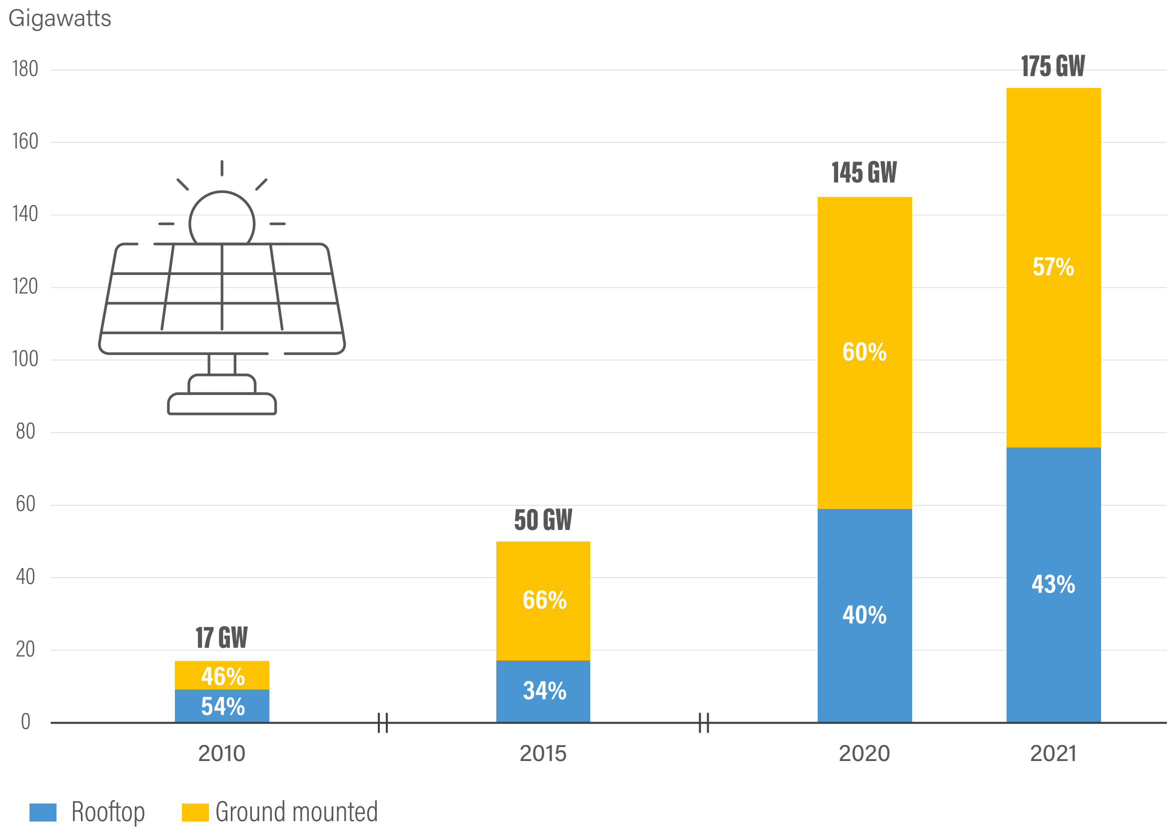
SOLAR PHOTOVOLTAICS (PV)

Solar photovoltaic technology converts sunlight into electricity using panels of semiconductor materials. Exposure of the semiconductors to sunlight excites electrons, generating a flow of electricity. Solar PV has experienced record growth (► see Figure 12), with annual capacity additions in 2022 increasing 37% relative to 2021[i], to bring the total installed capacity to around 1,185 GW.[310] Solar PV ranks third after hydropower and wind power for annual renewable electricity generation.[311]

Total annual generation from solar PV is expected to increase 25% annually on average to 2030, to reach around 7,500 TWh.[312] To meet global scenarios for net zero emissions, 551 GW of capacity will need to be added by 2030, growing from around 1,185 in 2022 to 5,400 GW of total installed capacity in 2030.[313]

Numerous guidelines and standards have been established to ensure the sustainability, efficiency and quality of solar PV systems.[314] The guide on *Mitigating Biodiversity Impacts*

FIGURE 12. Annual Additions of Ground-Mounted and Rooftop Solar PV Capacity, 2010, 2015, 2020 and 2021



Source: *IEA. See endnote 310 for this chapter.*

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[i] Comprising 25% utility-scale installations and 54% decentralised solar PV.


Eneco Group

Associated with Solar and Wind Energy Development, developed by the International Union for Conservation of Nature (IUCN) in collaboration with The Biodiversity Consultancy, provides extensive guidelines for project developers, including tools to assess potential impacts and to apply the mitigation hierarchy at all stages of solar and wind project development.[315]

The Solar Sustainability Best Practices Benchmark, developed by SolarPower Europe, identifies best practices, establishes benchmarks and provides practical guidelines.[316] Areas covered include carbon footprints, circularity, supply chains, biodiversity, social acceptance and human rights. In addition, the benchmark adopts some certification schemes – such as ISO 14001 for environmental management – as best practices or requirements for procurement tenders.[317] The complementary Solar Stewardship Initiative brings together 50 organisations to advance the sustainability of solar power value chains (► see Energy Justice chapter).[318]

The Spanish Photovoltaic Union (UNEF) has launched a Certification of Excellence in Sustainability, which is tailored to ground-mounted solar PV plants and aims to acknowledge projects that adhere to the highest standards of social and environmental integration.[319] Independent assessors evaluate socio-economic aspects, such as local employment and community benefits, alongside biodiversity preservation. The focus is on enhancing local environments, possibly creating nature reserves. Developers must exceed legal requirements and adhere to circular economy principles for responsible end-of-life disposal and recycling.[320]

✔

Solar PV deployment, when integrated with existing uses, completely avoids additional demands for land.

Land Use

Solar PV deployment can completely avoid additional demands for land when integrated with existing uses. This includes: mounting PV systems on rooftops; integrating them into carpark facilities and transport infrastructure; installing them alongside existing transmission lines and transport routes; and co-deploying them with hydropower and agriculture (including bee keeping and pasture).[321] Solar PV can add value to otherwise unused or degraded land, including brownfields[i], landfill sites and degraded agricultural land.[322] In Chernobyl, Ukraine, a 1 MW solar plant was built on land contaminated by the meltdown of a nuclear reactor.[323]

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[i] For example, at unused mining sites and abandoned industrial areas.

PV systems can be integrated on rooftops, carparks and transport infrastructure; sited alongside transmission lines and transport routes; and co-deployed with hydropower and agriculture.

Calculations of land use for ground-mounted solar PV installations are complex and varied, due to the difficulty of accurately accounting for the area covered by supporting infrastructure (roads, electrical equipment, and spacing between devices) and factoring in the multi-use potential. Insolation levels also affect calculations: projects at high latitudes may require 50% more land than projects deployed in moderately sunny locations – and up to three times as much land as projects located near the equator – to generate the same amount of electricity.[324]

Land-use estimates for ground-mounted solar PV plants in Europe suggest a footprint of 870 hectares per TWh annually.[325] In the United States, estimates are around 1,300 to 2,000 hectares per TWh annually for facilities over 20 MW and 1,200 for those under 20 MW, based on estimated or anticipated generation.[326]

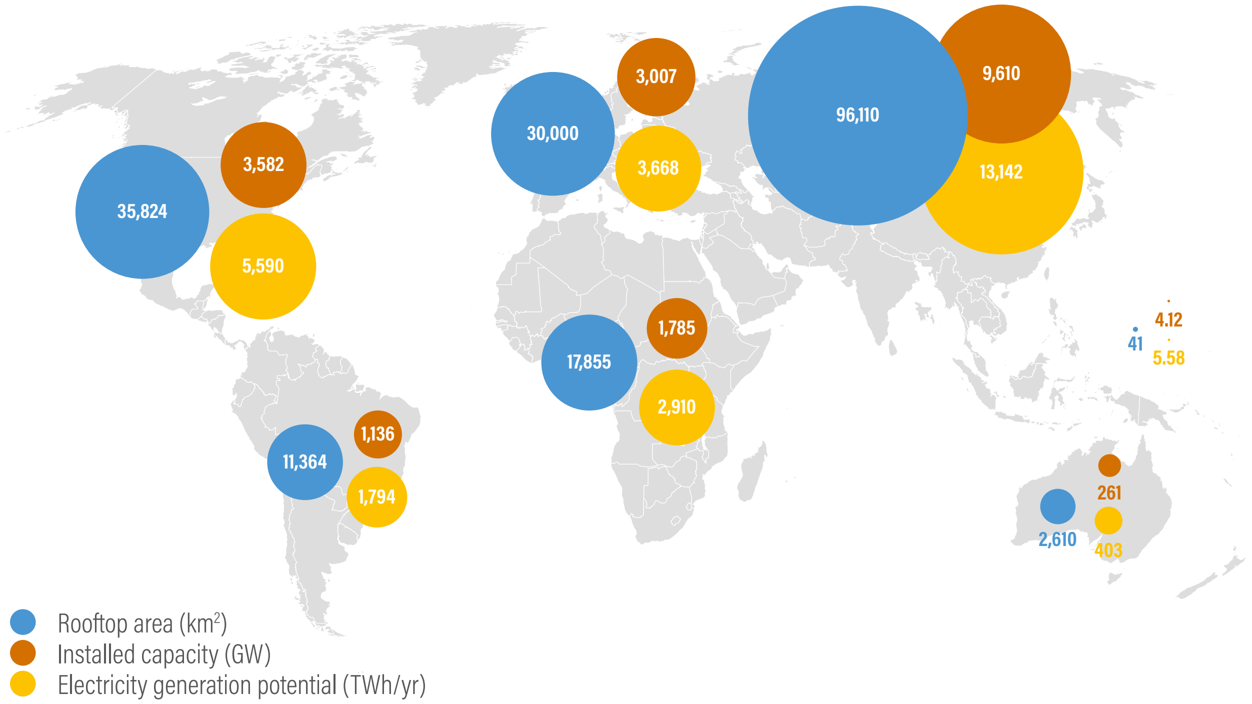
In some regions, regulations expressly exclude solar PV installations from agricultural land or other designated areas,[327] and the trend has been increasingly to integrate solar PV into existing land uses or infrastructure.[328] Some large-scale ground-mounted solar PV facilities have nonetheless been deployed on land that was not yet occupied by other human activities.[329]

The long-term impacts of ground-mounted solar PV on soil quality have not yet been widely studied and are context-specific. One study in France found that the shading from the panels can affect soil temperature and soil CO_2 effluxes[i],[330] A Chinese study of a PV plant located in a desert found that the effects from shading can make a positive contribution to restoring vegetation.[331] A long-term study of a 500 MW facility in India suggests that the soil shading and electric current may transform salty marshland into cultivable soil by reducing salt content and boosting bacterial growth.[332]

Solar PV on Rooftops and Existing Infrastructure

By one estimate, rooftop solar PV has a total energy generation potential of 27 petawatt-hours per year – more than the overall electricity demand (from all sources) globally in 2018.[333] Rooftop solar PV has the highest potential in Asia, North America and Europe[ii] (► see Figure 13).[334] Due to Africa's comparatively smaller building stock, the continent has the third lowest rooftop solar potential among regions despite its solar resources; even so, the combined potential of West and North Africa exceeds that of India.[335]

FIGURE 13. Assessment of Global Technical Potential of Rooftop Solar PV Power Generation, 2021



Note: The figure shows the estimated maximum electricity generation that can be derived from a given rooftop area, as well as the existing built-up extent in 2015.

Source: *based on S. Joshi et al., 2021. See endnote 334 for this chapter.*

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[i] Releases of CO_2 into the atmosphere from natural and human-induced sources.
[ii] Based on factors such as the built environment, population and solar insolation.

Solar PV systems can be integrated into buildings or other urban infrastructure such as carparks and noise barriers, as well as into streets and vehicles. Where land is scarce, such dual use could mitigate conflicts over land use. A 2022 French law requires owners of carparks over 1,500 m² to install solar PV systems.[336] The United States holds huge potential for solar PV in carpark areas: such facilities covered as much as 5% of urban land as of the early 2000s and an estimated 0.47% of the total contiguous land area as of 2012.[337] For ground-mounted solar PV, single- or dual-axis tracking systems require less land area than do fixed-tilt systems to generate the same amount of electricity.[338]

Floating PV

Solar PV can be deployed on the surface of water bodies such as lakes, the sea, reservoirs and rivers. In 2018, the global installed capacity of floating solar PV was 1.3 GW, representing only a fraction of the projected global potential of 400 GW.[339] Water-cooled floating PV panels perform better than those on land, with 10-15% higher efficiency at freshwater sites and 13% at sea (although the harsh conditions present engineering challenges).[340]

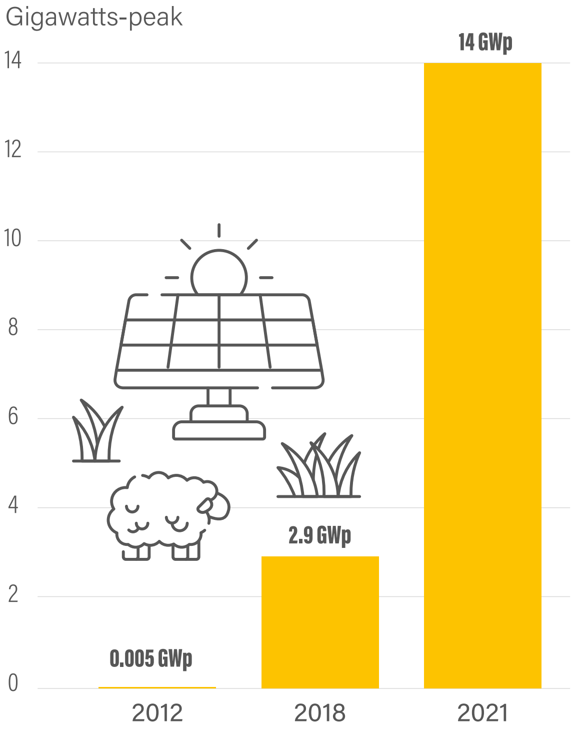
Floating PV deployments have been shown to lower the water temperature, reduce evaporation and provide shading that reduces algal blooms.[341] In Jordan, a floating solar PV installation reduced annual water evaporation 42% compared to open water bodies.[342] Floating solar PV can be combined with hydropower, on reservoirs behind dams, and with offshore wind projects, improving efficiency by sharing infrastructure and logistics, as well as allowing for co-ordination on electricity output (for example, to respond to peak demand or stabilise fluctuations).[343]

Challenges associated with floating solar PV include the need for corrosion-resistant materials and robust anchoring systems to withstand currents and waves as well as water-level fluctuations. Installations must be designed to avoid and minimise harm to water bodies and aquatic biodiversity.[344] Among negative impacts, the reduced sunlight and lower temperatures associated with floating PV can decrease photosynthetic activity, leading to phytoplankton loss, less oxygen, and impacts on wildlife (for example, by changing bird feeding habitats).[345] This also can lead to multiplication of algae[i].[346] Further effects on water chemistry, the atmosphere and other biological impacts have been postulated, but more research is needed, particularly on impacts on different kinds of water bodies.[347]

Agrivoltaics

By combining solar generation and agriculture, agricultural PV (agrivoltaics) preserves valuable farmland for food production or pasturage, reducing competition for land and potentially providing a range of environmental benefits. Farmers can use the energy on site (such as for food processing, water pumping or refrigeration) and generate additional income by selling surplus electricity.[348]

FIGURE 14. Global Agrivoltaic Installed Capacity, 2012, 2018 and 2021



Source: *Fraunhofer ISE. See endnote 349 for this chapter.*

Supported by targeted policies, the global installed agrivoltaic capacity increased from around 5 MW in 2012 to at least 14,000 MW in 2021 (► see Figure 14).[349] China has installed 12,000 MW of capacity, while Japan is home to more than 3,000 systems.[350]

France is the European agrivoltaic leader, having launched several funding programmes and tenders.[351] The government has adopted standards that define agrivoltaics and provide a structure and process for decision making and project development.[352] This includes installation guidance (building permits, expert opinions, insurance) and the role of technical partners in planning, construction, installation and operation. Europe's total potential agrivoltaic capacity is an estimated 51 TW.[353] Solar PV modules can be used to collect rainwater and reduce irrigation demand by up to 20% by limiting evaporation.[354] This can be especially beneficial in arid and semi-arid regions (► see Sidebar 4).[355] In Kenya, research reported improved growth of cabbage, maize and other vegetables, while other studies identify potential improvements in water productivity of certain crops.[356] Shading can benefit animals, too, with one study showing decreased heat stress in cows.[357]

Agrivoltaic systems can be designed to enhance native habitats and conserve biodiversity through the planting of pollinator-friendly native flora.[358] This can create "solar-pollinator" habitats that support insect diversity, facilitate pollination, and provide pest control, ultimately boosting local agricultural production.[359]

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[i] The impact on algae and aquatic ecosystems can be complex and vary depending on the specific local conditions. While decreased sunlight may limit the photosynthetic activity of some algae, lower temperatures could favour the growth of different types of algae, potentially leading to increased overall algal abundance.

Sidebar 4. Innovative Agrivoltaic Systems in Mali and The Gambia

An innovative project in Mali and The Gambia is using a holistic approach to assess the technical, social and economic viability of a "triple land use" system for energy, food production and water management. The project brings together agricultural research, socio-economic strategies and solar energy expertise to highlight the challenges and opportunities of sustainable agrivoltaic systems and to better understand the food-water-energy nexus.

An interdisciplinary consortium of German, Malian and Gambian partners plans to establish five agrivoltaic systems by June 2024 (► see Figure 15), including a 200 kW peak demonstration deployment and four 50 kW peak demonstrations. The modules are V-shaped to enable rainwater harvesting and will be installed at a height of 2.5 metres, which can increase output while also enabling light agricultural machinery to pass below.

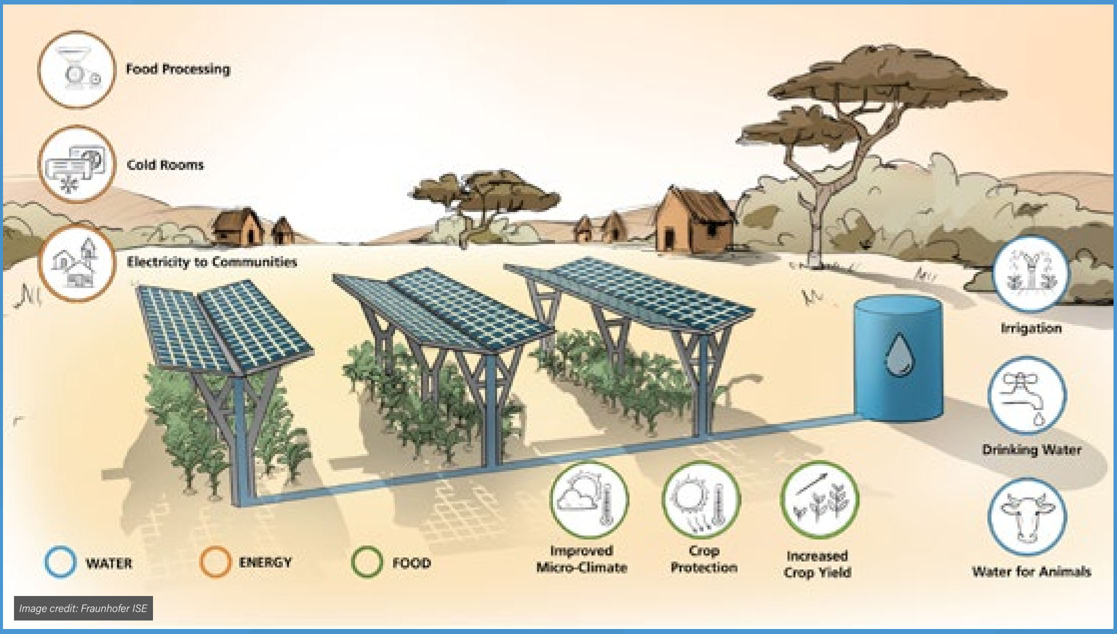
The collected water will be stored in storage tanks at a minimum height of 5 metres, which then will be distributed using solar-powered pumps. The modules shade the crops below, and researchers will study potential effects of both physical protection and reduced evapotranspiration on crop yields, including onions, tomatoes, potatoes, okra and green beans. The productive use of the energy generated by the agrivoltaic systems is achieved by integrating cold storage in Mali and in at least one site in The Gambia, as well as post-harvest processing equipment (e.g., milling and oil-press machines) in The Gambia.

The project's community-based approach entails extensive communication between local partners and community members, including participatory schemes and studies of social acceptance. Focus groups and workshops with local farmers and other stakeholders aim to ensure that local interests, conditions and factors are considered and influence the conceptualisation of the agrivoltaic systems, with an emphasis on developing sustainable business models and capacity building. In both countries, local organisations will be established to oversee long-term operation and maintenance, with financial stakeholders and community members being equally involved in decision making.

The project remained in the early implementation stage as of May 2023 due to the impacts of the COVID-19 pandemic. Lessons can nonetheless already be learned, particularly regarding the conflicting interests of public and private organisations, the need for risk mitigation and the challenges of securing investment from participating African companies.

Source: *See endnote 355 for this chapter.*

FIGURE 15. Proposed Agrivoltaic Systems in Mali and The Gambia



Source: *Fraunhofer ISE.*

Werner Slocum / National Renewable Energy Laboratory

There remains a need for caution, careful siting and thorough environmental impact assessment. Agrivoltaics might not be suitable for all crops, and shading could alter the microclimate, affecting air circulation, humidity and other conditions.[360]

Water Use

As with other energy technologies, the manufacturing and operation of solar panels consumes water resources, with requirements varying by technology as well as project scale and location. Studies estimate an average consumptive water footprint of between 0.02 and 1.1 litres per kWh.[361] Water demand can be as low as 0.25 to 1.5 litres per kWh when deployed on rooftops and making use of newer technologies[i].[362]

The solar industry is working on ways to reduce water use during the manufacturing process.[363] Many operators of ground-mounted solar PV systems rely solely on rainwater to clean the panels. In some areas, the accumulation of dirt and dust can necessitate more regular cleaning to maintain efficiency (especially large-scale plants and those in arid regions).[364] Globally, an estimated 38 billion litres of water are used for cleaning solar PV panels.[365] A study in India estimated operational and maintenance demands of between 7 and 20 litres of water per kW.[366] Waterless technologies such as mechanical brushes and drones are being tested for panel cleaning, and dust-repellent panels (using electrostatic repulsion) are being developed to save water and reduce operation costs.[367]

✓ Well-designed agrivoltaic systems enhance native habitats and conserve biodiversity through the planting of pollinator-friendly native flora.

Floating solar systems can reduce the rate of evaporation from water bodies, including canals and hydropower reservoirs, by shading water from the sun; in turn, the water cools solar panels, increasing their efficiency.[368] A floating solar PV system in India reportedly avoids the evaporation of an estimated 325 million litres of water per year (► see discussion on floating solar PV, p. 61).[369]

Pollution and Greenhouse Gas Emissions

Solar PV has no emissions during operation.[370] Most greenhouse gas emissions associated with solar PV result from manufacturing processes that rely on fossil fuels. However, solar panels offset these emissions within 4-8 months of operation and have an average lifetime of 25-30 years; as a result, the life cycle emissions of solar PV are far lower than those of fossil fuels per unit of energy generated.[371]

The types and amounts of pollution attributed to solar PV depend on factors such as the technologies used and the manufacturing process. Wide ranges in estimates are due to variations in energy demand during production and in the output of the panels over their lifetimes, which is determined mainly by local weather conditions.[372] The results of life cycle analyses are highly sensitive due to diverse inputs (► see Box 2, p. 21).

Most emissions over the life cycle of solar PV installations are from the production of inputs, such as the extraction of raw materials, and the manufacture of solar cells and assembly of panels.[373] The Intergovernmental Panel on Climate Change (IPCC) reports median life cycle emissions from utility-scale solar PV installations of 48 grams of CO_2 equivalent per kWh, with all of these emissions attributed to the production of panels and associated infrastructure.[374] Other life cycle studies estimate that greenhouse gas emissions range from 11 to 226 grams of CO_2 equivalent per kWh, with a median of 43 grams of CO_2 equivalent per kWh.[375] Technology improvements and decarbonisation of production processes have the potential to further reduce greenhouse gas emissions.

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[i] For example, a European study identifies the low end of this range for cadmium telluride (CdTe) systems and the upper end for monocrystalline silicon (mono-Si) systems.


Prashanth Vishwanathan / IWMI

As global solar PV deployment continues to increase, so too will the volume of panels ready for decommissioning. One study estimates that panels reaching the end of their 30-year lifetime could amount to 78 million tonnes of raw materials and other valuable components by 2050.[376]

The solar panel manufacturing industry is actively adopting circular solutions to minimise waste and environmental impact. Manufacturers are working on sustainable production processes and reducing potentially polluting by-products.[377] This commitment extends to companies across the solar PV value chain, with some pledging to reduce the carbon footprint of their products through initiatives such as the UltraLow-Carbon Solar Alliance, established in 2020.[378]

Regulations in various jurisdictions are promoting take-back programmes and prohibiting electronic waste in landfills to create a sustainable supply of panel waste for economically viable recycling.[379] Recycling programmes also are growing.[380] For example, the Solar Energy Industries Association created a programme to establish a recycling network throughout the United States, and recycling is becoming more prevalent across the country.[381] The development of dedicated recycling is advancing in Europe, and a handful of facilities also operate in other regions.[382] In addition, increasing the efficiency and lifespan of solar PV panels and supporting the small but growing market for second-hand panels can reduce relative waste and pollution (► see discussion on circularity, p. 97).

Biodiversity

Solar installations that are integrated into the built environment have few direct negative effects on biodiversity.[383] Elsewhere, solar farms can provide shelter and protection for wildlife, as well as predictable land use, which can support biodiversity.[384] With appropriate land management techniques, there are opportunities to increase pollinator biodiversity: one study found that replacing maintained grass with native plants can triple the number of pollinators.[385] A solar PV farm in the US state of Minnesota used pollinator-friendly plants to cool the microclimate, reduce erosion and improve groundwater storage.[386]

Agrivoltaics is an increasingly popular way for solar installations to co-exist with and support the ecosystems in which they are sited (► see earlier discussion). Where facilities use land formerly dedicated to intensive farming, they can rejuvenate soils by reducing chemical inputs and promoting fertile soil recovery while also conserving freshwater.

Utility-scale solar PV installations nonetheless can necessitate some vegetation clearing and top-soil removal, and can affect the water flow (including blocking rainfall from some areas and dousing others with heavy run-off). In some instances, land preparation activities cause habitat fragmentation, hindering the movement of species, removing natural hiding places and reducing food availability.[387] Careful siting and management ensure that solar projects do not contribute to land conversion and biodiversity loss.[388]

CONCENTRATING SOLAR THERMAL POWER (CSP)

Concentrating solar thermal power (CSP) systems utilise mirrors or lenses to concentrate sunlight onto a heat transfer fluid, which is then used to generate steam and drive turbines to produce electricity. CSP technology has evolved significantly in recent years, with the development of parabolic trough, linear Fresnel, power tower and dish systems.[389] Wide divergences exist in approaches and in the results of life cycle assessments and other studies for CSP. Further research is needed to better understand the potential impacts and benefits.

Land Use

Data on real electricity generation from CSP systems with regard to land use are scarce. Estimates compiling sources from the EU and the United States suggest a range of 780 to 1,930 hectares per TWh annually.[390] Other studies that consider CSP plants more globally suggest a median land-use intensity of 1,300 hectares per TWh annually.[391] Interesting possibilities exist to co-ordinate the growth of renewables with infrastructure projects that save land, for example by co-locating wind and solar CSP plants.[392]

Water Use

CSP plants use water for steam to spin turbines, for cooling, and for cleaning mirrors (especially in arid and semi-arid regions). The total water demand for CSP varies depending on the technology used and on whether plants use water cooling or dry cooling technologies (such as dry air or water-air hybrid cooling). These alternatives reduce water demand by as much as 90%, but this lowers efficiency and increases costs.[393] Ongoing projects are testing innovative approaches such as using treated effluent from wastewater plants; this could decrease water demand without impacting efficiency and cost, although possible locations are limited.[394]

One study estimates that a 50 MW CSP plant using water cooling would use 1.6 million m^3 of water annually, whereas an equivalent plant using dry cooling technology would use around 400,000 m^3.[395] US estimates from 2010 are in the range of 0.08 to 3.79 litres per kWh.[396] Another study, from 2015, estimated that CSP used to produce heat and electricity consumed between 0.4 and 7.9 litres per kWh.[397] Among CSP technologies, dish engines require the least amount of water, although they require more land.[398]

CSP plants are mostly suitable for semi-arid and arid areas with high solar irradiation, but these areas often face water scarcity. In the United States, some CSP developers have bought water rights from other sectors, such as agricultural users, to meet their water demands.[399] Attention to local conditions is essential to avoid conflict with other uses and to minimise impacts on water availability and quality.[400]

> Emissions from the manufacturing of solar panels are offset within 4-8 months of operation.

Pollution and Greenhouse Gas Emissions

Life cycle emissions from CSP facilities range from an estimated 11 to 241 grams of CO_2 equivalent per kWh, with an estimated median of 28 grams.[401] This represents a 97% reduction from the median life cycle CO_2 emissions of coal-fired power plants.[402] The limited data show large variances depending on the size of the plant, geographic location, and technology, as well as on the supply chain.[403]

Wet-cooling technologies can lead to a risk of contaminating water with hazardous chemicals. Water also can become contaminated during construction and mirror cleaning (if using chemicals).[404] The heat transfer fluid used in parabolic trough systems) presents a potential pollution hazard.[405]

Biodiversity

CSP installations may lead to habitat loss and displacement, disruptions to animal movement, and altered hydrology and water quality, with further potential indirect effects resulting from changes in land use.[406] Wastewater from CSP towers is concentrated in evaporation ponds, potentially attracting wildlife and posing risks of poisoning and drowning, although this is easily mitigated with simple fencing and wire meshing. The concentrated light energy also may pose a direct risk to birds. Thorough assessment of sensitive areas during a project's design, and careful project siting, can help to avoid or mitigate these impacts. Experts also recommend reserving buffer zones between sensitive areas and power plants, with varying distances depending on the type of plant and the wildlife habitat.[407]

SOLAR THERMAL HEATING

Solar thermal systems contributed around 6% of renewable heat in 2022, serving various applications.[408] Such systems are a prominent source of hot water for individual buildings, and large-scale deployments are increasing, particularly for district heating systems.[409] At the end of 2022, the global operational solar thermal capacity was 542 gigawatts-thermal (GW_{th}).[410]

The number of dwellings using solar thermal technologies for water heating reached 250 million in 2020.[411] To meet scenarios for net zero greenhouse gas emissions by 2030, an estimated 290 million new solar thermal heating systems[i] will need to be

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[i] This includes 170 million new solar thermal systems using standard technologies and 120 million new solar thermal systems using emerging technologies. See endnote 412 for this chapter.

US Department of Energy Solar Decathlon

installed this decade.[412] In 2022, an estimated 571 large-scale solar thermal plants were operational (the majority to provide district heating), with a combined capacity of 2.2 GW_{th}.[413]

The environmental impacts of solar thermal are limited, with low land and water use and considerable emission savings over fossil fuel heating systems.[414] The development of novel technologies and applications promises to further improve efficiency and reduce resource demands.[415] Nascent solar thermal cooling systems can use natural refrigerants such as water and ammonia, offering a way to meet rapidly growing demand for air conditioners. Photovoltaic thermal systems (PVT) can integrate solar heat and electricity production, enhancing energy yields and reducing land requirements. Solar steam plants can provide heat for industrial processes, such as metal refining.[416]

Small-scale solar thermal collectors, typically integrated into existing infrastructure or rooftops, require minimal land. The 20 largest solar district heating systems, each with an average capacity of 22.6 megawatts-thermal (MW_{th}), require around 3.5 hectares of land per MW_{th}.[417] The largest solar district heating plant, in Silkeborg, Denmark, commissioned in 2016, covers around 15.7 hectares of land with a capacity of 110 MW_{th}, or 0.14 hectares per MW_{th}.[418]

Solar thermal systems use minimal water, mostly for occasional maintenance and collector cleaning. The systems also operate with minimal greenhouse gas emissions and pollution. Emissions may occur during manufacturing and installation, depending on the materials and energy sources used. Currently operational solar thermal systems offset around 145 million tonnes of CO_2 annually.[419] Solar thermal technologies are likely to require fewer rare elements and hazardous substances compared to other technologies, thereby mitigating biodiversity impacts through reduced resource demands and pollution.[420]

WIND POWER

Wind power is a mature technology[i] that, along with solar PV, has long been seen as a key technology in the energy transition.[421] Wind energy is the second leading source of renewable electricity after hydropower.[422] An estimated 89 GW of wind power was installed in 2022, and the total operating capacity globally at year's end was around 906 GW (93% terrestrial; 7% offshore). Capacity is expected to triple by 2030, surpassing 3,500 GW.[423]

Wind power generated an estimated 1,870 TWh of electricity (around 7% of total generation) in 2021, and this is projected to reach 8,000 TWh by 2030, in line with most scenarios for the energy transition.[424] For wind energy to make its full contribution to net zero greenhouse gas emissions, generation would need to increase by an average of 18% annually to 2030.[425]

International wind industry associations as well as national governments have produced best practice guidelines to assist planning authorities and developers in the siting and deployment of wind energy projects, and to advance environmental, social and economic considerations in sustainability assessments, operation and maintenance of wind farms.[426]

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[i] Floating offshore wind turbines, where the turbines are mounted on floating platforms anchored to the seabed, are in the pre-commercial stage.

The Global Reporting Initiative has published a range of voluntary standards that are relevant to managing the potential environmental effects of wind turbines, including on materials, waste, effluent, emissions, biodiversity, and local and Indigenous communities.[427] Wind manufacturers and operators can use these standards in their sustainability reporting.[428]

IUCN has collaborated with The Biodiversity Consultancy to develop extensive guidelines for project developers that include tools to assess potential impacts, manage environmental risks and apply the mitigation hierarchy across the entire life cycle.[429] The European Maritime Spatial Planning Platform has published a guide for offshore wind developers.[430]

Land Use

Onshore wind energy does not generally require extensive excavations, and, once operational, turbines have a small footprint. In most cases, the land located between turbines can still be used for other purposes, such as farming or grazing (however, this is context dependent, as sometimes land is excluded for security reasons or because of land planning regulations).[431]

Estimates of the direct land-use footprint of wind power typically include only the area covered by the turbines and access roads, although some studies also include the spacing between turbines.[432] Calculations based on a randomised sample of US facilities larger than 20 MW suggest a median direct footprint for onshore wind power of 130 hectares per TWh annually.[433] When spacing is included, the estimated footprint increases to as much as 12,000 hectares per TWh annually.[434] However, land use is highly context dependant, and calculations generally do not reflect possibilities for multi-use sites.

To further minimise land demands, turbines can be deployed on degraded land and co-deployed with other activities. Wind turbines can be installed on agricultural land with minimal crop damage, enabling the co-production of energy and crops and potentially providing an additional source of income.[435] The electricity produced can be used for agricultural purposes (such as powering irrigation systems), reducing a farm's operating costs and improving yields. Specific agriculture-compatible poly-winged turbines have been developed to draw water from the deep soil.[436]

Small-scale wind turbines can be installed on rooftops or atop towers on developed land close to existing structures. Although at a much lower level of maturity, rooftop wind turbines also have the potential to complement solar energy in the urban environment.[437] A study in the Netherlands found that wind turbines mounted on high-rise buildings could potentially generate around 170 GWh annually in the country.[438]

> ✓ In most cases, the land located between wind turbines can be used for other purposes such as farming or grazing.

Offshore wind turbines occupy space on the seabed and surface, as well as on land (for infrastructure such as electrical connections and sub-stations), while maritime regulations and safety zones also may increase the demands for space.[439] Research is ongoing to optimise the siting of turbines offshore and reduce space requirements.[440]

Offshore installations can co-exist with fishing, aquaculture, tourism and other activities.[441] Multi-use platforms can integrate these diverse uses and could eventually also incorporate tidal turbines and wave energy converters.[442] Such initiatives face legal and regulatory barriers, as well as challenges in mediating with existing users.[443] Authorities have a key role to play in expanding multi-use by reviewing legislation, overseeing multi-sector dialogues and developing marine spatial plans.[444]

Water Use

Wind farms have low water requirements, with a small amount being used during manufacture. During operation, some components (such as generators, transformers and inverters) require water cooling, while turbine blades are often sufficiently cleaned by rain.[445]

Pollution and Greenhouse Gas Emissions

In contrast with fossil fuel power plants, which emit greenhouse gases throughout their life cycle, emissions from wind farms are limited to the manufacturing and construction phases. The estimated CO_2-equivalent life cycle emissions per kWh are as low as 12 grams for onshore wind energy and 19 grams for offshore wind energy.[446]

Production of components, such as steel blades and towers, can be energy intensive.[447] The industry is actively addressing the challenge of reducing the carbon footprint of these manufacturing processes.[448] The transport of wind turbine components to their installation sites can result in emissions as well as temporary disruptions to local communities and ecosystems.

The level of noise emitted by wind installations is generally low, although context-specific factors can affect how this noise is perceived, such as the nature of the noise (continuous, modulating) and the surrounding environment (e.g., turbines sited in a typically quiet area).[449] Preconceptions about the technology and its impacts have been shown to greatly increase reported impacts.[450]

There is no evidence of direct effects of wind turbines on human health.[451] Research shows that reported issues are related to

Joan Sullivan / Climate Visuals

the lived experience of nearby residents, perceiving noise or visual annoyance, which can produce stress and lead to sleep disturbances.[452] Some studies highlight that annoyance tends to be lower when residents participate in the siting decisions and when other surrounding noise is loud (e.g., roads), and other research suggests that the reported impacts can be influenced by pre-existing beliefs ("nocebo" effects).[453]

Shadows cast by rotating turbine blades ("shadow flicker") are assessed during the planning phase and can be mitigated through careful site design and planting of vegetation that shield affected buildings.[454] Wind turbine manufacturers are integrating shadow flicker protection systems that strategically pause generation based on several customisable parameters (such as time, sun position and meteorological data) and provide sound protection for bats.[455]

The typical lifetime of a wind farm is around 20-25 years, and few have been fully decommissioned to date. Some wind farms are expected to begin decommissioning soon, and more than 50,000 tonnes of blades are projected to be decommissioned annually in Europe by 2030.[456] Various efforts are under way to provide guidance and to develop standardised protocols.[457] This would help to ensure that impacts first identified during deployment do not recur during decommissioning.[458] When decommissioning offshore wind farms, a key consideration is whether to leave structures such as foundations in place, particularly where marine habitats have developed.[459] This will depend on the relevant regulations and contract terms between the public authority and the developer.[460]

Governments and the industry have implemented policies, commitments and new technologies to address such impacts. For example, countries have established zoning laws and ordinances that influence how and where wind projects can be sited, including minimum setbacks from buildings and water bodies, as well as limitations on noise and shadow flicker.[461]

Manufacturers also are focusing on achieving carbon neutrality in their own operations as well as international supply chains, including by setting emission targets.[462] Many are working to eliminate non-recyclable waste from manufacturing, operation and decommissioning (► **see circularity section in Materials chapter**).[463] The uptake of novel steel processes is expected to further mitigate the carbon footprint of steel production, and investment in this area is increasing.[464]

Biodiversity

Given their low emissions and small land and water footprint, wind turbines represent a net biodiversity gain when compared to fossil fuels.[465] Turbine manufacturing nonetheless requires raw materials such as balsa wood[i], steel, and critical minerals, thereby implicating activities with associated biodiversity impacts.[466]

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[i] Balsa wood has been associated with deforestation concerns, and the industry has been exploring alternatives, such as growing it domestically or replacing it with other materials.

Despite their small footprint, turbines can affect wildlife during construction and operation. Some animals may avoid the project area, an effect that has been found to scale with turbine size.[467] Such behavioural changes could potentially affect interdependent species and alter ecosystem dynamics.[468] For example, researchers have observed wolves avoiding wind farms at distances of 6 kilometres, while other species, such as tortoises, benefit from such deterrence of predators, as well as from reduced road traffic and increased resource availability.[469]

Careful siting and design of wind farms can mitigate impacts on biodiversity and promote nature-positive benefits.

Birds and bats have been the focus of most studies to date.[470] Researchers have assessed risks from collisions and, in the case of bats, changes in surrounding air pressure.[471] Overall, turbines are currently very low on the list of threats to bird life.[472] However, some species may be at higher collision risk[i].[473] Migratory birds may alter course to avoid turbines, requiring them to use more energy or to abandon rest stops.[474]

Modern wind turbines can detect birds and automatically slow or stop operations to reduce collisions, and migration forecasts can be used for planning.[475] Restricting operations during warm, low-wind periods also reduces risk, and there are promising indications that simply painting one turbine blade black can reduce collisions.[476] Bats can be deterred from approaching turbines using ultrasonic waves.[477]

Careful siting and design – such as locating wind farms away from migration corridors, ridges and ecologically sensitive areas – can go a long way towards mitigating biodiversity impacts and promoting nature-positive benefits.[478] Dedicated tools are available to assess risk and to avoid or mitigate potential impacts (such as BirdLife International's AVISTEP tool), and a range of impact-specific mitigation measures are commonly deployed.[479] Partnerships among industry, government agencies and other stakeholders can help to ensure that the risks are effectively mitigated.[480]

Offshore wind power can cause changes to marine habitats that may entail both positive and negative impacts. Site-specific risks to biodiversity, such as barriers to species movement and alteration of water and sediment flows, can be minimised through project development that prioritises monitoring, conservation and restoration of local ecosystems.[481] This may include characterising the initial state of the target area, identifying potentially affected species, and setting out environmental objectives.[482] More research is required to understand the potential cumulative effects of multiple wind installations and other activities.[483]

Offshore wind farms can act as an artificial reef, potentially creating up to 2.5 times more habitat for fish, barnacles and other organisms (although this habitat may not always be suitable for endemic species).[484] Turbine foundations provide a conducive environment for coral growth because they are located at depths where the temperature circulates between warmer surface waters and cooler deep waters, and where there is enough sunlight for corals to grow, without the high temperatures that cause bleaching.[485] ReCoral, a joint project of Danish energy company Ørsted and reef restoration start-up Reefy, has helped settle incubated coral reef larvae on the foundations of offshore floating turbines in Chinese Taipei.[486]

Active fishing methods are often prohibited in the vicinity of offshore wind farms, thus providing a respite for fish and discouraging highly destructive trawling.[487] If installed on areas that were previously trawled, offshore platforms can encourage ecosystem recovery, providing favourable habitat for heavily fished and other vulnerable species.[488]

Offshore construction generates noise from seabed preparation, installation of foundations and a temporary increase in boat traffic.[489] Most existing offshore turbines use fixed foundations that are installed at depths less than 50 metres.[490] Pile driving for foundations can be disruptive to species sensitive to sound and can cause them to temporarily avoid areas around the construction site.[491] However, misinformation has sometimes overstated these impacts or assigned causality to offshore wind turbines without evidence.[492] Solutions include sound reduction at the source, such as installing cushions on machinery (an emerging technology) and attenuating sound using a "bubble curtain".[493]

Certain seabird species tend to avoid wind farms.[494] The low-frequency sound they generate may disturb some marine animals, although detailed studies are lacking.[495] Studies in the North Sea found no significant impacts on several regionally abundant marine mammals (harbour porpoises, grey seals and harbour seals) but noted impacts to fish due to habitat change, noise and electromagnetic fields around cables.[496] Proper environmental impact assessment and sensitive siting can mitigate these impacts.

In terms of **decommissioning**, most wind turbine components are recyclable, and the industry is actively developing innovative pathways to circularity (► see Materials chapter).[497] In 2021, ENGIE recycled more than 96% of components from the

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[i] Such as raptors, larger and less agile birds, and those that fly in lower light conditions.

Karsten Wurth / Unsplash

decommissioning of its first grid-connected wind farm in France, and emerging chemical processes can enable recycling of blade materials.[498] Turbine blades also are being repurposed for second-life applications, such as bike shelters and park benches (► see Materials chapter).[499]

ELECTRICITY NETWORKS

Grids, the backbone of electricity systems, are attracting much-needed attention as the energy transition advances. To ensure that there is sufficient capacity and flexibility to efficiently connect renewables and maintain security of supply, there is a pressing need for grid modernisation and digitalisation, as well as the construction of new grid corridors.[500]

More than 3,000 GW of renewable energy projects, including 1,500 GW in advanced stages, were stuck in grid connection queues worldwide as of 2023 (owing both to physical limitations in the grid and to regulatory and permitting issues).[501] Such significant delays could lead to a 58 gigatonne increase in cumulative CO_2 emissions by 2050, increased reliance on fossil fuels, and economic risks (due to power outages, which already cost around USD 100 billion annually).[502]

Since not all lines can be placed underground due to high costs, technical factors, and potential environmental concerns, it is inevitable that additional grid infrastructure will require additional land.[503] Indirect impacts also occur, particularly from raw material extraction, manufacturing, assembly, recycling, disposal and transport.

Policies and initiatives are emerging to harmonise electric grid modernisation with environmental conservation. The European Grid Declaration – a collaboration between the Renewables Grid Initiative (RGI), environmental organisations and grid operators – promotes co-operative efforts to mitigate adverse impacts of new power lines and grid infrastructure, particularly during initial project phases.[504]

Biodiversity

Sensitive deployment according to well-documented good practices – including impact assessment, integrated planning and mapping, and adaptive management – can greatly reduce impacts to biodiversity.[505] However, when poorly managed, the expansion of the grid can result in habitat modification, disruptions to landscape connectivity, and biodiversity loss.

Power lines can pose risks to birds and other animals through electrocution and collision with wires.[506] The risks vary according to location and species type. Areas of high risk for birds include wetlands and coastal areas, as well as meadows.[507] For migratory birds, flyways and migration routes (for example, river valleys and mountain passes) are areas of high risk.[508] Renewable energy grid infrastructure may also pose localised threats to aquatic habitats and wildlife.[509]

Identifying risks and assessing the vulnerability of species to power lines is critical. Evaluating wildlife mortality helps create databases to map sensitivity and risk, enabling targeted prevention and action. Electrocution risk can be eliminated by insulating charged components and improving design of high-risk pylons. Collision can be prevented by applying bird flight diverers or "wire markers" to power lines. In Germany, RGI and BirdLife provide an online portal for reporting the finding of a dead bird, which is then analysed by an ornithologist.[510] In Belgium, collision risk maps, based on the most recent knowledge on bird distribution, are used to quantify the risk of bird collision with power lines and to mitigate risks across the country.[511]

Increasing interest and supportive policies worldwide have spurred advancements in research and technology to reduce grid-related environmental impacts. For instance, BirdLife International has developed AVISTEP (the Avian Sensitivity Tool for Energy Planning) to help assess avian sensitivity concerning renewable energy infrastructure.[512]

Integrated vegetation management (IVM) is a method that grid operators can use to boost biodiversity while ensuring system security by preventing trees from touching the power lines – and potentially causing a blackout or fire. IVM is an alternative to conventional vegetation management, whereby grid operators create "green corridors" and support local species diversity. Key activities include restoring grasslands, selectively pruning trees for forest edges, revitalising heathlands and peat bogs, digging new ponds and controlling invasive plants.[513]

> ✓ Integrated vegetation management of electricity grids can boost local species diversity while supporting grid development.

Biodiversity-friendly vegetation management has proven to be 1.4 to 3.9 times more cost-effective than traditional methods over a three-decade period.[514] A project in Spain demonstrated that altering the vegetation around electric transmission towers can enhance biodiversity, benefiting invertebrates, small mammals, birds, and their species diversity, potentially aiding in the reconnection of fragmented populations.[515] Additional strategies such as "grid grazing", where animals such as sheeps or native horses graze around grid infrastructure, contribute to soil fertility, biodiversity and fire prevention by removing excess vegetation.[516] These approaches offer benefits to both biodiversity and local stakeholders, and may even reduce costs in some cases.

Table 2 provides a summary of solutions for maximising the benefits of renewable energy technologies in the areas of land use, water use, pollution and greenhouse gases, and biodiversity.

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TABLE 2. Solutions for Maximising the Benefits of Renewables

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Land Use	Multiple uses of land and water: technologies co-existing with agricultural land, or other land uses or leisure activities	Agrivoltaics Integrated solar PV and wind energy Floating PV Agroforestry and multi-cropping practices for bioenergy Integrated Vegetation Management (IVM) for electricity grids Hydropower dams used for irrigation, leisure, fishing, etc. Onshore wind power with agriculture / pasture Offshore wind power with aquaculture / fishing / leisure ***Examples:*** *French government's standards for agrivoltaics development* *French law requiring owners of carparks over 1,500 m^2 to install solar PV systems* *FAO's Bioenergy and Food Security Approach* *Biogas Done Right initiative*
	Use of existing infrastructure	Rooftop solar PV and wind Use of carparks, roads, railways, etc.
	Use of degraded land and waste streams	Technologies integrated into degraded / unproductive land Bioenergy sources from waste streams ***Example:*** *In Chernobyl, Ukraine, solar plant built on contaminated land*
	Location and scale	Small-scale run-of-river hydropower plants
Water Use	Strategic siting and technology selection	**For bioenergy** Siting crops in areas with ample rainfall Choosing crops that require minimal water **For geothermal** Closed-loop binary-cycle units **For hydropower** Run-of-river hydropower plants Matching generation to demand and adjusting water release strategies Underground pumped storage and off-stream water storage **For solar PV** Waterless cleaning technologies (e.g., mechanical brushes) Dust-repellent panels Floating PV **For solar CSP** Dry and hybrid cooling systems
	Use of wastewater and rainfall	Use of wastewater for irrigation of bioenergy crops and for solar CSP cooling Use of rainfall for cleaning solar panels
	Regulations constraining water use	Regulations in São Paulo state (Brazil) establishing limits on water use for sugarcane cultivation
Pollution and Greenhouse Gas Emissions	Reducing supply chain emissions	Reducing supply chain emissions by increasing the use of renewables in supply chains Use of green steel
	Circular solutions for end-of-life (re-use / recycling)	***Examples:*** *Solar Energy Industries Association's programme to establish a recycling network in the United States* *Ultra Low-Carbon Solar Alliance* *See also circularity section in Materials chapter*
	Policies and incentives mandating limitations on greenhouse gas and pollutant emissions and aimed at preventing deforestation	**For bioenergy** Use of crop and forest residues, post-consumer organic residues and agricultural / forestry by-products, methane from landfill sites, and farm wastes and organic liquid effluents Agricultural practices that avoid land-use change Regulating the use of fertilisers and pesticides ***Examples:*** *EU Renewable Energy Directive* *US Renewable Fuel Standard* *Brazil RenovaBio programme* Stringent air quality regulations *EU Ecodesign standards*

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Biodiversity	Strategic spatial planning and careful siting	**For all technologies** Environmental Impact Assessments Identification of vulnerable species and migratory routes Applying the mitigation hierarchy **For electric grids** Integrated Vegetation Management (IVM) **For bioenergy** Avoiding monoculture plantations and introduction of invasive species Avoiding raw materials produced on land with high biodiversity value including primary forest, biodiverse wooded land and biodiverse grassland ***Examples:*** *IUCN and The Biodiversity Consultancy guidelines* *Guide from the European Maritime Spatial Planning Platform for offshore wind developers* *BirdLife International's AVISTEP tool* *RGI's collision map* *EU Renewable Energy Directive (RED III)* *GSAP's sensitive site selection*

Industry Guidelines and Certifications Discussed in the Chapter

- Global Bioenergy Partnership
- Geothermal Sustainability Assessment Protocol
- Hydropower Sustainability Standard
- Solar Sustainability Best Practices benchmark (SolarPower Europe)
- Solar Stewardship Initiative
- Certification of Excellence in Sustainability (Spanish Photovoltaic Union)
- Voluntary reporting standards of the Global Reporting Initiative for wind energy developers


Abir Abdullah / Climate Visuals Countdown

Sidebar 5. Renewable Solutions to Reduce Energy and Water Use in Agriculture

Energy, water and land are interdependent yet increasingly scarce resources. Powering the agriculture sector alone uses 30% of the world's energy production, and the sector accounts for 80-90% of global freshwater use and nearly 38% of global land surface use. Despite these high inputs, the agri-sector remains highly inefficient, with one-third of the global harvest spoiled or discarded along the value chain each year.

Energy is required along the entire agri-value chain, from food production, to post-harvest processing, to storage, to consumption by end users. However, most developing countries lack access to reliable, affordable and sustainable energy to power many agri-processes. Renewable energy has great potential to energise the agri-value chain, prevent food loss, and increase the incomes and resilience of farmers.

Food Production

Energy is needed to produce inputs such as fertilisers and machinery for agricultural production. A key renewable solution to replace the use of chemical fertilisers is bioslurry[i], a by-product of biogas and wastewater plants that has huge market potential. Over the long term, bioslurry can improve soil quality[i] and the water retention of soil, decreasing water demand.

Pumping water for irrigation is an energy-intensive activity. In many developing countries, solar-powered irrigation systems can be a reliable option for smallholder farmers to reduce reliance on expensive fossil-powered pumps. Solar pumps can increase farmers' productivity and income by reducing the drudgery related to water pumping and enabling irrigation in drier months. They also provide a reliable and continuous electricity supply that is not affected by national power cuts or load shedding. However, solar pumping needs to be linked with smart water management and accounting techniques to avoid exploitation and contamination of groundwater resources.

A study on the sustainable expansion of solar water pumps in sub-Saharan Africa concluded that the market is too small to cause a major threat to groundwater resources in the short or mid-term. However, as the technology advances and as droughts become severe (affecting groundwater recharge), it could cause higher risk to groundwater resources.[i]

Post-Harvest Processing and Storage

After harvest, food goes through different processes such as milling, grinding, drying and cooling before being consumed. The energy-intensive process of milling is done mostly by women, who pound or grind food by hand or use diesel-powered mills. In rural Africa, households spent USD 50 annually on average using diesel-powered hammer mills. However, renewable-powered technologies are changing the landscape. For centuries, farmers have used water- and wind-powered mills, but private companies are now piloting smaller, affordable solar mills.

The energy required for food drying, one of the oldest methods of food preservation, depends on various factors such as the type, moisture content and quantity of the food. Increasingly, farmers are using solar- and biomass-powered mechanical dryers to help conserve their produce post-harvest, reducing food waste. Appropriate cooling technologies also can reduce food spoilage by as much as 23% in developing countries. Solar-powered cooling solutions are being piloted in the market to meet the needs of smallholder farmers.

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[i] The definition of bioslurry should be thoroughly looked at, as sewage sludge can carry chemical pollutants depending on how it is produced. The US state of Maine banned the use of sewage sludge to prevent chemical pollution.

Source: *See endnote 517 for Ecosystems chapter.*

Petra Schmitter / IWMI

Sidebar 6. Renewable Solutions in the Water Value Chain

Energy is required for wide-ranging activities along the water value chain, from extraction and pre-treatment to distribution and post-treatment. In 2014, the water sector accounted for 4% of global electricity consumption, including for pumping, distribution, treatment, desalination and re-use. In the United States, the electricity use for wastewater treatment alone represented 40% of the total water sector demand. Rising energy demand from the water sector will put additional pressure on land and biodiversity. The use of renewables along the water value chain has the potential to meet this demand and also lessen the impact.

Water Supply

Worldwide, more than 2.1 billion people do not have access to clean drinking water, and more than half of the global population lacks proper sanitation facilities. Energy can play a key role in increasing water provision in both rural and urban areas. Renewable solutions such as solar-powered pumps and electricity from mini-grids can facilitate water pumping for both irrigation and drinking water. In 2016, water supply accounted for 42% of the total energy demand of the water sector, showing the enormous potential for integrating renewables in the sector. In the United States, 14-19% of the total residential electricity demand in Southern California in 2007 was solely for the extraction and transmission of water to the final consumer.

Depending on the source, the energy supply can also be a financial burden for water authorities and facilities. In the United States, 30-40% of municipal energy bills are for the energy used to provide public drinking water and for wastewater utilities. For municipalities in India, water supply forms the largest share of operating budgets. Hence, renewable energy sources that have lower water footprints and are cost efficient can help to reduce energy bills while also having a positive impact on water demand and the carbon footprint.

Wastewater Treatment

As much as 80% of the wastewater generated worldwide is dumped directly into the ecosystem without treatment. Because treatment can reduce the bulk of organic matter and its related methane emissions, wastewater that is left untreated can release up to three times more emissions than conventionally treated wastewater. In total, the wastewater sector accounts for 3% of global greenhouse gas emissions.

Treating wastewater is an energy-intensive process, requiring energy mainly for aeration (52%), processing of biosolids (30%) and pumping (12%). In the United States, electricity demand from wastewater treatment facilities accounts for 40% of the total electricity demand from the water sector. Globally, around 25% of the water sector's electricity demand in 2014 was for wastewater treatment, with this share reaching 42% in industrialised countries.

The potential to use renewables to power wastewater treatment facilities is significant. By replacing fossil-based systems, renewable energy can reduce the energy bills of both households and treatment facilities. At Calera Creek Water Recycling Plant in the US state of California, solar energy provides 10-15% of the plant's energy needs, saving USD 100,000 per year.

Producing biogas from wastewater sludge can provide energy both for the plant and for export. A wastewater treatment plant in Xiangyan City, China converts sludge to biogas and uses half of the gas for on-site energy needs, with the rest purified and compressed to fuel municipal taxis, creating additional income for the plant. In the United States, the Western Lake Superior Sanitary District uses biogas generated in the treatment facility to power 35% of its operation, saving on energy bills and enabling greater autonomy. In the San Francisco Bay Area, the East Bay Municipal Utility District, which manages wastewater for 650,000 customers, recycles biodegradable food waste in its wastewater treatment plant to produce biogas, and also has solar installations and hydropower. Since 2012, the plant has been able to meet 100% of its energy needs with renewables, and even sells excess power to the Port of Oakland. In Chennai, India, the wastewater plant meets 98% of its electricity demand from biogas generated from the solid waste.

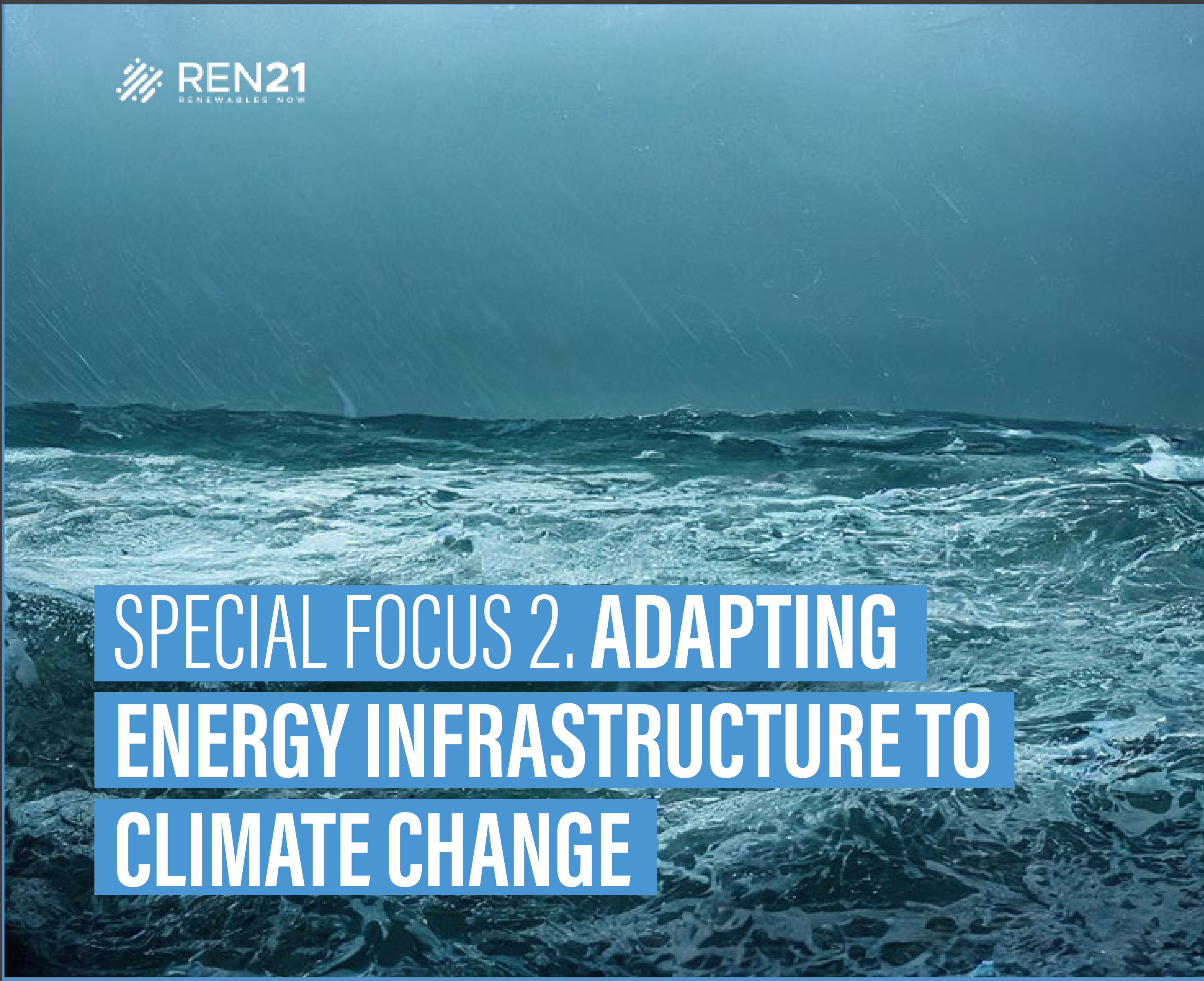
Desalination

Desalination – the process of removing salt from sea and brackish water – is energy and cost intensive, requiring on average 23 times more energy and costing 4-5 times more than surface water pumping. Globally, desalinated water accounted for 0.6% of the total water supply (65.2 million m^3 per day) and around 0.4% of total electricity consumption in 2013.

However, the energy required depends on the technology and water type. Multi-stage flash (MSF) technologies require 80 kWh of thermal energy and 2.5-3-5 kWh of electricity per cubic metre of seawater desalination, while reverse osmosis technologies need 3.5-5 kWh. Desalination of brackish water requires only one-tenth the energy compared to seawater. Around 36% of the operational expenses for seawater desalination are for covering the energy costs of pumps that power water filtration.

The Middle East and North Africa region is home to 38% of the global desalination capacity and consumes 90% of the thermal energy used globally for desalination plants – with the largest demand coming from the United Arab Emirates and Saudi Arabia. As water demand in the region increases, the energy demand for desalination plants is projected to rise from 5% in 2020 to almost 15% in 2040, a three-fold increase. Renewables can play a pivotal role in meeting this energy demand. In 2016, renewables provided only 1% of the total energy supply for desalination in the Middle East, showing potential for greater deployment.

Source: *See endnote 518 for Ecosystems chapter.*



SPECIAL FOCUS 2. ADAPTING ENERGY INFRASTRUCTURE TO CLIMATE CHANGE

ADAPTATION TO CLIMATE CHANGE is an essential pillar of the Paris Agreement, as certain climate impacts are assumed to become unavoidable in the coming decades. Given the interdependence of local, national and international urban infrastructure systems – including transport, energy, water supply, sanitation, buildings and telecommunications – these systems could become increasingly vulnerable to climate-related impacts. Although the scope and scale of climate impacts remains highly uncertain, the scientific community has identified key trends on which future assessment can be based, such as rising temperatures in the lower atmosphere and sea surface, increases in sea-level rise and reductions in topsoil wetness.

The development of infrastructure and energy systems has generally assumed climatic conditions that reflect the recent past. However, scientific consensus regarding climate-related impacts suggests the need to account for a new set of conditions when designing, operating and maintaining existing and planned energy infrastructure. This in turn highlights the need for climate-resilient considerations in both public and private sector energy policies and climate adaptation plans.

Although the scientific community has only recently begun studying the impacts of climate change on the energy sector, it is apparent that variations in climate could affect both energy production (renewable and non-renewable) and supply, as well as energy demand and the physical resilience of energy infrastructure. More frequent or intense extreme weather events such as heat waves, wildfires, cyclones, floods and cold spells can damage energy infrastructure, resulting in disruptions to energy supply and difficulties in managing demand. Climate impacts could also reduce the efficiency of power generation facilities.

Water Security as a Critical Issue

Since 2015, the World Economic Forum has listed "water crisis" as one of the top five risks for livelihood and overall impact. Water was considered to be a major point of conflict in 45 countries as of 2017, mainly in the Middle East and North Africa. Declines in water availability and increases in climate-induced disasters such as drought, heat waves and flooding will directly affect the energy security of many countries. Coastal energy infrastructure, such as oil refineries, liquefied natural gas terminals, and nuclear power stations, faces even higher risks from climate-related impacts such as sea-level rise, flooding, erosion and extreme weather events.

In 2020, 87% of the electricity generated from thermal, nuclear and hydropower facilities worldwide depended directly on water availability. One-third (33%) of the thermal power plants that rely on fresh water for cooling are in high-water-stress areas, as are 15% of nuclear power plants (a share expected to rise to 25% in the next 20 years). For hydropower, 11% of the existing capacity is in high-water-stress areas, and around 26% of existing dams and 23% of projected dams are in river basins that have a medium to very high risk of water scarcity.

In summer 2022, heat waves and drought in Europe affected the availability of water for both hydropower production and the cooling of thermal power plants. Many hydro and thermal power plants in Italy either halted or completely shut down their operation, and water reservoirs in Portugal had only half the capacity of seven years prior. France had to temporarily close down some nuclear reactors to avoid flushing large amounts of warm water into rivers, which themselves had warmed due to the heat waves.

India has experienced similar power constraints related to increasing droughts and delayed monsoons. Thermal power plants (powered by coal, natural gas and nuclear energy) supply 83% of India's electricity demand, but 40% of these plants are in arid and semi-arid areas. These areas are already experiencing water shortages, and the situation is likely to worsen. Between 2013 and 2016, power outages due to water shortage decreased the revenue of businesses in India by USD 1.4 billion.

Overall, the global energy supply is highly vulnerable to the availability of water, and these impacts will be greater for countries with large shares of hydro and thermal power in their energy mix. Access to water supply is also impacted if there is no reliable supply of energy for water pumping, treatment or distribution.

As climate change accelerates, the water-energy nexus will become more pronounced at the regional, national and international levels, resulting in greater conflict among countries over shared water resources (such as transboundary rivers). Water and energy security will be a major challenge not only in water-stressed areas, but also in areas with ample water supply that are increasingly impacted by climate change and associated disasters. In turn, the lack of reliable energy supply will directly impact the water value chain.

To increase resilience and integrate good practices in the planning, design and operation of hydropower projects, a Hydropower Sector Climate Resilience Guide was developed in 2019 by the International Hydropower Association with support from the European Bank for Reconstruction and Development and the World Bank's Korea Green Growth Trust Fund partnership. The guide offers a methodological approach to identify, investigate and manage climate risks.

In addition to mitigating climate change and its consequences on water scarcity, transitioning to a renewable energy mix could reduce water stress and increase energy security. The amount of water used to generate solar and wind power is much lower than for fossil fuel- and nuclear-based power plants. Renewables can also help water utilities become energy autonomous while reducing their energy costs.

Prioritising Adaptation and Climate-Resilient Energy Infrastructure

As of early 2023, only 40% of the climate action plans submitted by governments to the United Nations Framework Convention on Climate Change prioritised adaptation in the energy sector, and investments have been criticised as being too low. Similarly, as of 2021, around a quarter of the member countries and associate members of the International Energy Agency did not have a national climate or energy plan that focuses on the climate resilience of energy systems. Efforts to close the service gaps in water and sanitation, transport, electricity, irrigation and flood protection will depend heavily on the goals and policy choices of low- and middle-income countries and will require estimated annual funding of between 2% and 8% of GDP by 2030.

Accounting for climate resilience in infrastructure planning requires the ability to anticipate, absorb, accommodate and recover from the effects of a potentially hazardous climatic event. A climate-resilient energy system is one that can adapt to and withstand the long-term changes in climate patterns while being able to operate under the immediate shocks from extreme weather events and to restore system function after an interruption. The IEA's Climate Resilience Policy Indicator is a key resource for assessing and sharing information on climate-resilient energy systems. The World Bank also offers measures, policies and financial support to promote energy resilience. Meanwhile, the Pan-European Climate database contains a large set of variables that can be used for modelling and planning the European electricity system while addressing climate impacts.

Source: *See endnote 519 for Ecosystems chapter.*

03

MATERIALS

03

MATERIALS

INTRODUCTION

The international community has widely recognised the urgency of phasing out fossil fuels. The extraction and use of these fuels, including coal, oil, and fossil gas, threatens the stability of the Earth's climate and results in air, water, and soil pollution, with severe impacts on ecosystems and human health.[1] Even so, as of 2021, fossil fuels accounted for 78.9% of the world's final energy consumption, with modern renewables accounting for only 12.6% and nuclear power and traditional biomass for 8.5% (► **see Figure 1, p. 18**).[2]

Fossil fuel and nuclear-based energy systems rely primarily on bulk materials such as cement and steel as well as on a continuous supply of fuels that are non-renewable and polluting. In contrast, renewable energy technologies, when deployed sustainably, can operate without the use of limited and harmful fuels.[3] However, transitioning from fossil fuels to renewables involves building new infrastructure for energy generation and storage, as well as adapting transmission infrastructures to handle a larger share of variable energy sources and increased electricity generation.[4] Many of the materials needed for this transition, including bulk materials, are already commonly used in electricity infrastructure.[5]

Renewable energy generation and energy storage infrastructure also require several minerals that so far have not been used widely in energy generation. Some of them are considered to be "critical resources", due to factors such as resource availability, the quality of ores, geopolitical considerations, and the potential social and environmental impacts associated with their extraction.[6] Although many of these critical materials are already being used in other applications, such as smartphones and hard drives, the energy sector is set to be a major driver of their demand.[7]

To reach the ambitious global target of net zero greenhouse gas emissions by 2050, a significant scale-up of renewables and related infrastructure is expected. According to one scenario, the annual deployment of renewable energy capacity required globally to achieve net zero emissions could be three to four times the 2021 level in every year until 2030.[8]

Predictions about future infrastructure and equipment requirements for renewables vary widely, depending on the scenario and on the variables being assessed. As renewable energy technologies evolve rapidly, key factors to consider include the material composition, the scale of deployment, the choice of sub-technologies, possible pathways for recycling and re-use, and assumptions about final energy demand.[9] Regardless of the scenario, it is clear that substantial amounts of certain materials will be required to build out the envisioned capacity for renewable generation, transmission and storage (► see Figures 16 and 17).[10] Notably, most of these materials can be re-used or recycled.[11]

The need for sufficient supplies of certain (sometimes rare) materials – such as lithium, cobalt and rare earth elements – has already begun to influence global supply chains, causing an economic shift among companies and governments.[12] Meanwhile, unregulated extraction and processing of minerals can have detrimental social and environmental impacts.[13] By gaining a more complete understanding of the challenges and opportunities related to materials supply for a future energy system based on renewables, it is possible to identify best practices for achieving the urgently needed energy transition in a sustainable manner.

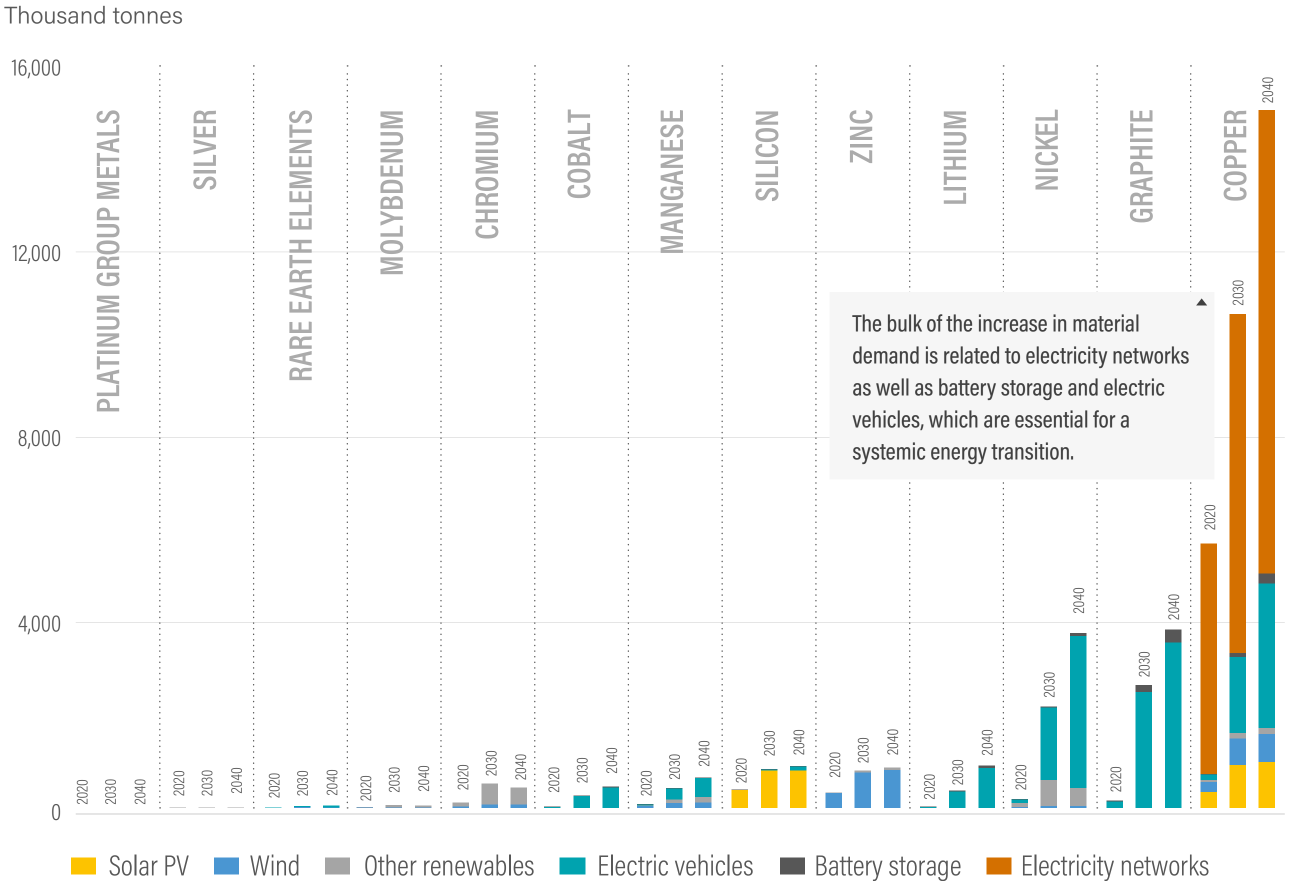
Solutions include technological choices, such as selecting components that avoid or minimise the use of critical minerals like lithium or rare earth elements; prioritising and promoting sustainable and secure sources of minerals; minimising the environmental and social impacts of extractive activities; and promoting circularity in material supply chains. Also key is reducing the overall demand for energy through greater energy efficiency and a sufficiency[i] approach (► see Special Focus 1 on energy sufficiency, p. 28).[14]

SCOPE OF THE CHAPTER

This chapter aims to provide an overview of the main challenges related to the materials needed to transition to a renewables-based energy system, as well as the potential solutions to overcome these challenges and to minimise the impacts of increased materials extraction. However, the chapter is not exhaustive, and data gaps may persist, opening the way to further research.

This chapter strives to cover the materials directly related to renewable energy technologies. It does not address the impacts of bulk materials such as steel and cement, which are used across many economic sectors beyond energy.

FIGURE 16. Projected Increases in Material Demand by Technology, IEA Sustainable Development Scenario for 2030 and 2040, Compared to 2020



The bulk of the increase in material demand is related to electricity networks as well as battery storage and electric vehicles, which are essential for a systemic energy transition.

Source: *IEA. See endnote 10 for this chapter.*

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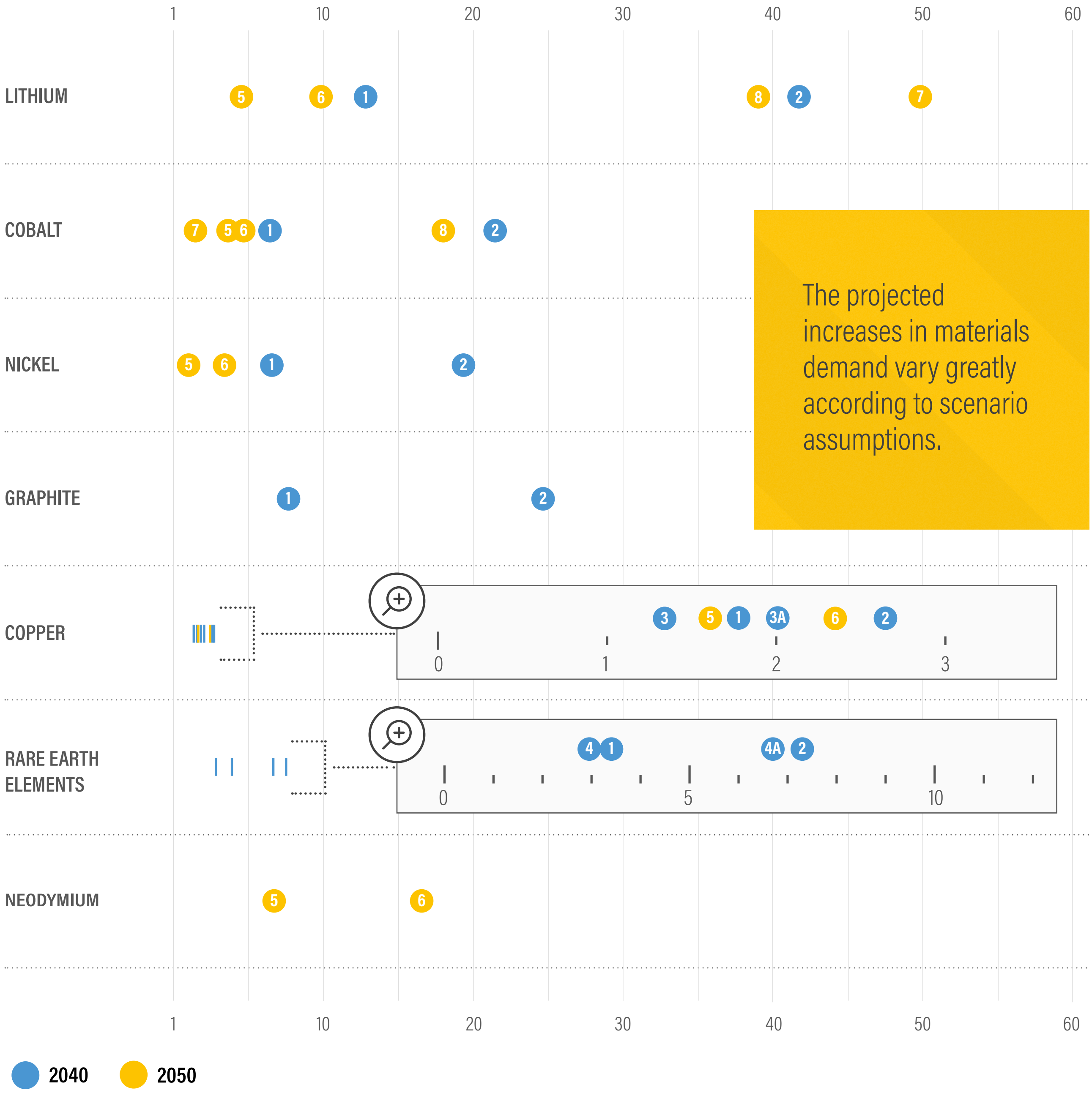
[i] Sufficiency involves a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries. See endnote 14 for this chapter.

FIGURE 17. Projected Increase in Demand for Selected Materials Under Several Scenarios for 2040 and 2050

Unit: multiplication factor from 1 (1 = 2020 demand by total volume)



The projected increases in materials demand vary greatly according to scenario assumptions.

1. IEA Stated Policies Scenario (STEPS) Base Case 2040
2. IEA Sustainable Development Scenario (SDS) Base Case 2040
3. IEA STEPS - higher share of aluminium in grids

3A IEA SDS - higher share of aluminium in grids

4. IEA STEPS - constrained REE scenario (gradual switch to non-magnet technologies)

4A IEA SDS - constrained REE scenario (gradual switch to non-magnet technologies)

5. IRENA 1.5°C Scenario - low estimation (increase in demand by 2050)
6. IRENA 1.5°C Scenario - high estimation (increase in demand by 2050)
7. OECM scenario 1 - total demand considering future technological changes and future recycling (annual demand in 2050 compared to 2019 production rates)
8. OECM scenario 2 - total demand with no changes in current technology and no recycling (annual demand in 2050 compared to 2019 production rates)

IEA = International Energy Agency
IRENA = International Renewable Energy Agency
OECM = One Earth Climate Model
(University of Technology Sydney)
REE = Rare Earth Elements

Source: *See endnote 10 for this chapter.*

Moreover, some renewable energy technologies, such as solar PV and wind energy, attract more attention due to their expected exponential growth in the coming decades and to the imminent decommissioning of older installations. Literature and experience-sharing are more widely available for these technologies than for technologies that are undergoing less-rapid development or use fewer critical materials.

Most of the studies, regulations and initiatives cited in the section on circularity relate to Europe and the United States. This does not mean that activity is not occurring in other regions, but rather reflects the fact that these two regions face similar timelines for the "first wave" of decommissioning of renewable energy installations in the near future. These regions have responded with industrial strategies and regulations, for which information is widely available. Other world regions have developed or may be developing similar strategies and could be highlighted in future REN21 research.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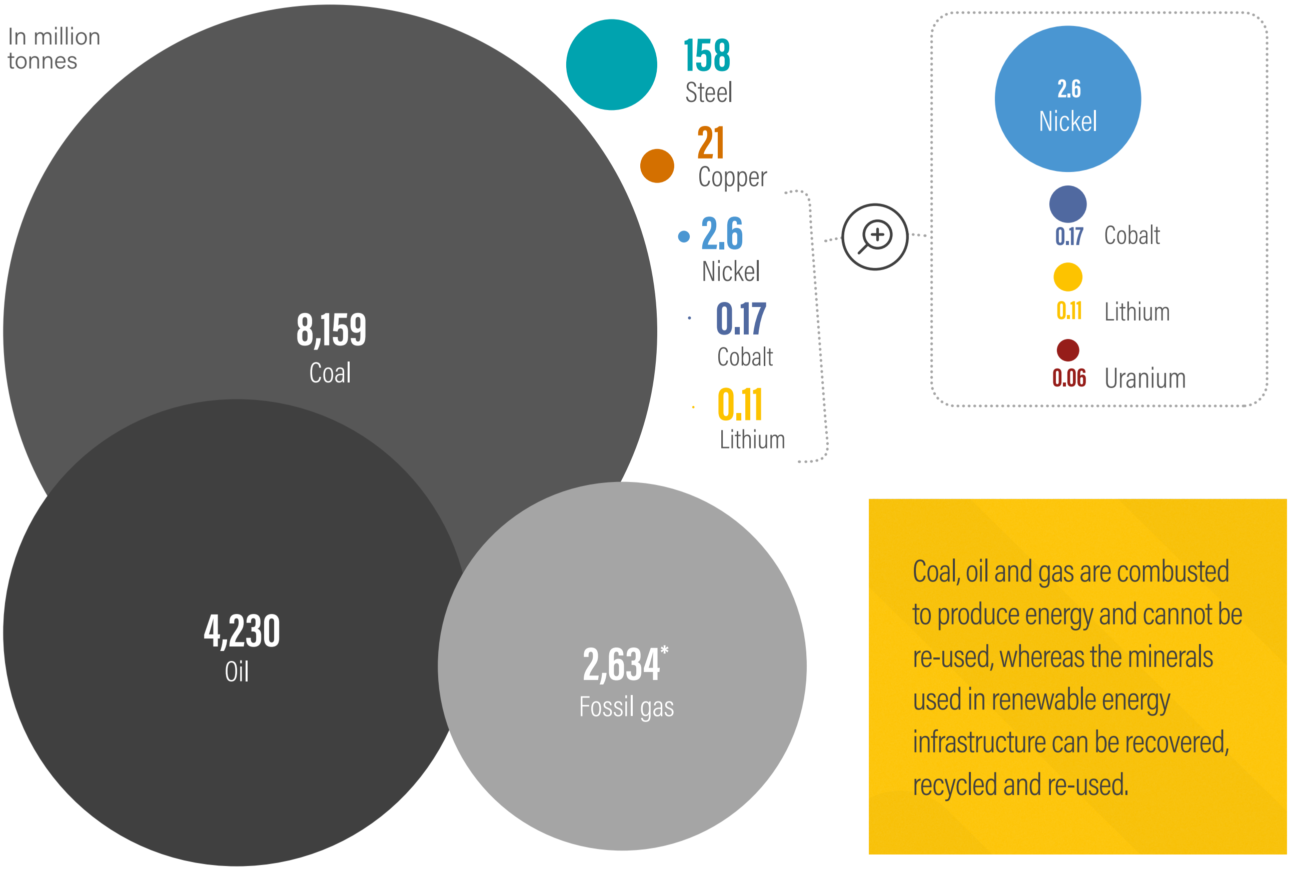
MATERIALS USED FOR FOSSIL FUEL AND NUCLEAR ENERGY SYSTEMS

Each year, around 8 billion tonnes of coal, 4 billion tonnes of oil and the equivalent of 2.6 billion tonnes of fossil gas are extracted from the Earth's land mass and sea floor (► **see Figure 18**).[15] In 2022, the use of these fossil energy sources resulted in the release of around 35 gigatonnes of CO_2 equivalent into the atmosphere.[16] In addition to being a major driver of global climate change, the extraction and combustion of fossil fuels results in pollution of the air, water, and soil, with wide-ranging impacts on ecosystems and human health (► **see Ecosystems chapter**).[17]

Wide variations exist in the material requirements for different types of energy generation. However, certain materials are common across multiple energy sources. In the case of fossil fuels, these include the materials used in electricity generation plants – such as steel, cement, copper, plastic and composite – and in the infrastructure for electricity transmission and distribution. Oil and gas extraction and distribution activities require drilling rigs, pipelines and tankers for crude oil transport, and refineries for fuel processing. Liquefied natural gas (LNG) requires additional processing and infrastructure. Coal extraction involves mining operations and requires transport infrastructure such as rail lines, highways, roads and shipping infrastructure.[18]

FIGURE 18. Annual Production of Selected Energy-Related Fuels and Minerals, 2021



Coal, oil and gas are combusted to produce energy and cannot be re-used, whereas the minerals used in renewable energy infrastructure can be recovered, recycled and re-used.

Note: Recovery rates from different ores and impacts of mineral extraction vary depending on extraction techniques. The numbers presented aim to provide an order of magnitude of mineral extraction and do not reflect all impacts in detail.

* 4,053 billion cubic metres converted to million tonnes considering density of fossil gas of 0.65 kilograms per cubic metre.

Source: *See endnote 15 for this chapter.*

Nuclear energy represented 10% of global electricity production in 2021 and accounted for 4% of the total primary energy consumption in 2022.[19] Nuclear power plants require enriched uranium as the fuel, use steel and concrete for the reactor and containment structures, and use boron as a neutron absorber. The fuel assemblies in the reactor are often encased in zirconium alloy tubes. Some nuclear plants use graphite as a moderator to slow down neutrons and enhance the fission process. Additional material requirements for the plants include copper, aluminium, stainless steel, insulation and wiring.

In 2021, around 62,496 tonnes of uranium were required to fuel the nuclear power plants in operation worldwide.[20] According to the International Atomic Energy Agency, as of early 2019 around 8 million tonnes of conventional uranium resources were still in the ground. [21] Plutonium, generated as a by-product within the reactor, accounts for more than one-third of the energy produced in nuclear power plants.[22]

Most non-renewable energy sources – such as fossil fuels and nuclear power – do not rely on materials deemed to be "critical", with the exception of copper and aluminium, which are needed mainly for grid connectivity. However, many of the materials and fuels used in non-renewable energy generation are associated with significant environmental and social impacts (► see Ecosystems chapter and Energy Justice chapter).

In addition to being a major driver of global climate change, the extraction and combustion of fossil fuels results in pollution of the air, water, and soil, with wide-ranging impacts on ecosystems and human health.

MATERIALS USED FOR RENEWABLE ENERGY SUPPLY

Renewable energy technologies require a diversity of minerals and other materials, many of which are deemed critical (► see Table 3).[23] The current and estimated demand for materials generally varies by technology, with more diverse needs for wind turbines, solar PV modules and energy storage systems. Copper is commonly a component of all renewable technologies, and the use of rare earth minerals such as dysprosium, neodymium, praseodymium and terbium is increasing, particularly in wind turbines. Cobalt, graphite and lithium are used mainly in battery storage applications.

TABLE 3. Materials Used for Different Renewable Energy Technologies

MATERIAL	BIOENERGY	ELECTRICITY NETWORKS	ELECTRIC VEHICLE ENGINES	ENERGY STORAGE	GEOTHERMAL	HYDROPOWER	CSP	SOLAR PV	WIND
Aluminium		●		●				●	●
Boron			●					●	
Brass									●
Cadmium								●	
Carbon fibre									●
Chromium					●				●
Cobalt				●					
Copper	●	●	●	●	●	●	●	●	●
Dysprosium (REE)									●
Gallium								●	
Graphite				●					
Iron			●	●	●	●			●
Lithium				●					
Manganese				●		●	●		●
Molybdenum					●				●
Neodymium (REE)			●						●
Nickel				●	●	●	●		●
Phosphorus				●				●	
Praseodymium (REE)									●
Selenium								●	
Silicon								●	
Silver							●	●	
Tellerium								●	
Terbium (REE)									●
Titanium	●				●				

Note: CSP = concentrating solar thermal power; REE = rare earth element.

Source: *See endnote 23 for this chapter.*

MATERIALS CRITICALITY

In several scenarios that meet the emission reduction goals outlined in the Paris Agreement, the demand for minerals is expected to surge to 2030 (► see Figure 16).[24] However, the expected supply from existing mines, and for projects currently under construction, is estimated to be able to meet only half of the projected lithium and cobalt demand and 80% of the copper demand by that year.[25]

The criticality of materials required for renewable energy manufacturing and infrastructure is not solely the result of a mismatch between future demand and potential supply. In addition to relative supply scarcity, factors defining "criticality" for these materials include long lead times for development of mining projects, high geographical concentration of production, declining resource quality, and environmental and social concerns.

> Factors defining "criticality" include long lead times for development of mining projects, high geographical concentration of production, declining resource quality, and environmental and social concerns.

SCARCITY OF SUPPLY

The rapid increase in demand for materials used for renewable energy technologies raises questions about the reliability of supply. While there is general agreement about the availability of mineral ore deposits in the long term, a possible scarcity issue relates to short-term availability – that is, to the potentially limited access to ore deposits in the near future.[26]

The demand for concentrated[i] materials (including cobalt, graphite and lithium), which are used by only a limited number of industries, has increased in the past few years. This is in contrast to the wide range of cross-cutting[ii] materials (such as concrete, iron, and steel, and minerals such as chromium, copper and molybdenum) that are needed across numerous technologies and thus have predictable demand levels and more robust supplies. Because the main industry players in minerals supply did not fully anticipate the surge of renewables, and because future technology evolutions carry some uncertainty, only a few established suppliers exist for the minerals specific to renewable energy.[27]


Matjaz Krivic / Climate Visuals

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[i] Concentrated materials are defined as those needed in one specific technology.
[ii] Cross-cutting materials are those needed across a range of technologies.

LONG PROJECT DEVELOPMENT TIMES FOR NEW EXTRACTIVE CAPACITIES

Despite the currently limited supply of some materials for renewable energy manufacturing, so far the global demand for these materials does not exceed the rate of extraction.[28] However, a US analysis projects that by 2025, the need for all minerals used in renewable energy technologies and battery storage (except for lead) will exceed the annual extraction and processing capacity of existing mining operations.[29] A review of 35 mining projects from 2010 to 2019 found that developing a new project takes on average 16.5 years – including 12.5 years for discovery, exploration and feasibility; 1.8 years for construction planning; and 2.6 years from construction to production.[30] When demand for a mineral ramps up quickly, such long project development times could result in extended periods of market rigidity and price volatility.[31]

HIGH GEOGRAPHICAL CONCENTRATION OF EXTRACTION AND PRODUCTION

For many of the materials needed for the renewable energy transition, production is more geographically concentrated than for oil and natural gas.[32] For cobalt, lithium, and rare earth elements, the top three producing countries control three-quarters of the total global supply.[33] China and the Democratic Republic of the Congo account for 70% of the global cobalt supply and for 60% of the global production of rare earth elements.[34] Similarly, Australia and South Africa account for more than half of the worldwide supply of lithium and platinum, respectively.[35] The level of concentration is even higher for processing. China controls more than 50% of processing and operations for cobalt, lithium and rare earth elements and more than 30% for copper and nickel globally.[36]


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When the production of a mineral is highly concentrated, its supply becomes more vulnerable to physical disruptions (earthquakes, extreme weather events, pandemics, etc.), political instability (corruption, conflicts, etc.) and regulatory events (such as the export restrictions implemented recently in Zimbabwe for lithium, in Indonesia for nickel ore and in China for rare earth elements).[37]

DECLINING RESOURCE QUALITY

In terms of criticality, the quality of mineral ores is generally of greater concern than the quantity. The ore quality for cross-cutting materials used for renewable energy technologies has declined greatly due to the rapid depletion of high-grade ores. For example, the average ore grade for copper decreased 25% between 2005 and 2015.[38]

Declining ore quality brings multiple challenges, including higher extraction and processing costs, waste volumes and air emissions (such as greenhouse gas and particulate matter emissions).[39] Extracting lower-grade ores requires more complicated technologies and greater energy use, leading to higher budgets and greenhouse gas emissions.[40] Refining lower-grade ores results in a significant increase in rock waste and tailings, also leading to higher costs.[41]

ENVIRONMENTAL AND SOCIAL CONCERNS

Rising demand for the materials, particularly minerals, required for renewable energy infrastructure and equipment triggers a rapid increase in mining activities, which can have severe environmental and social consequences if not adequately remediated. Environmental concerns include greenhouse gas emissions, land-use change and contamination, water use and contamination, and waste management.[42] Accompanying these issues are numerous social concerns associated with mineral extraction and processing, among them poor working conditions, especially in artisanal and small-scale mining operations.[43] Serious human rights abuses such as child labour, forced labour and land grabbing have been reported in the mineral extraction value chain, together with violence and repression of environmental defenders.[44]. **(► For more on the social impacts of mining, see the Materials Extraction section.)**

CRITICAL MATERIALS FOR THE RENEWABLE ENERGY TRANSITION

In addition to the global factors influencing materials criticality, countries and companies often establish their own criteria for determining criticality. These include factors such as import dependence (the ratio of imported to exported materials), material prices, and specific geographical or technical requirements that are unique to a country or region (such as geopolitical risks, distance to producer countries, difficulty of substitution with accessible resources, and technological advancements).[45] Furthermore, competing end-uses exist for many of these critical minerals (► see Table 4).[46]

As of November 2022, 14 countries and the European Union had defined criticality and identified the range of minerals they deem critical (► see Table 5).[47] At least a dozen specific minerals are considered critical by a majority of these countries/regions, including lithium (11 countries and the EU), cobalt (9 countries and the EU), rare earth elements (9 countries and the EU), manganese (10 countries), nickel (9 countries), chromium (8 countries) and graphite (7 countries and the EU).[48]

Copper, a crucial mineral for all renewable energy technologies, is viewed as critical in 7 of the 15 countries/EU.[49] Iron and nickel, commonly found in many of the technologies listed in Table 4, are considered critical in 6 and 9 countries, respectively.[50] More than a third of the countries/EU consider as critical the availability and reliability of the complete list of mineral requirements for battery energy storage, including aluminium, cobalt, copper, graphite, iron, lithium, manganese, nickel and phosphorus.[51] Minerals necessary for electricity networks, as well as for hydropower facilities and bioenergy infrastructure, are deemed critical by five or more countries/EU.[52]

An increasing number of countries also have identified the need for access to a secure supply of components at other levels of the value chain of renewable energy technologies, such as manufacturing (► see Box 4).[53]

Box 4. Increasing Renewable Energy Manufacturing to Support Global Competitiveness and Resilience

While looking to secure mineral supplies, countries also have sought to ensure that their manufacturing capacity is ready to ramp up the deployment of renewable energy technologies and infrastructure in a timely manner. China has led in renewables manufacturing for more than a decade, but other countries and regions such as India, the United States and the EU are introducing policy incentives to support domestic production and to diversify the global supply. These policies aim to increase the competitiveness of domestic manufacturing and could result in an unprecedented expansion of renewable energy manufacturing outside of China in the next five years.

In 2022, India launched the Production-Linked Incentive Scheme and the United States passed the Inflation Reduction Act to offer financial incentives to boost the confidence of local manufacturers about product demand, resulting in more ambitious expansion plans. The EU's Net-Zero Industry Act seeks to increase the region's capacity to build technologies that support the transition to net zero energy. It aims to simplify the regulatory framework to boost the EU's manufacturing capacity for these technologies to at least 40% of annual deployment needs by 2030.

All of these policies strive to accelerate progress towards 2030 climate and energy targets, create better market access for clean energy technologies, attract investments, and create quality jobs, boosting countries' industrial competitiveness and energy system resilience.

Source: *See endnote 53 for this chapter.*

TABLE 4. Other End-Uses of Selected Critical Materials Used for Renewable Energy Supply and Electric Vehicles

Cobalt	**Lithium**	**Copper**	**Neodymium**
carbides and diamond tools	air treatment	consumer goods	automotive
catalysts	aluminium	construction	electrical equipment and electronics
magnets	ceramics and glass	electrical equipment and electronics	
pigments and inks	construction	industry	
superalloys	lithium-ion batteries (non-electric vehicle)	infrastructure	
	lubricants	power generation, distribution and transmission	
	metallurgy	transport and mobility	
	pharmaceuticals		
	polymers		

Source: *See endnote 46 for this chapter.*

TABLE 5. Critical Minerals for Developing Renewable Energy Infrastructure and Equipment, as Determined by Country/Region

MATERIAL	Number of countries that deem it critical	Australia (2022)	Bolivia (2022)	Brazil (2021)	Canada (2021)	China (2016)	Colombia (2012)	European Union (2020)	Finland (2011)	India (2016)	Japan (2020)	Peru (2021)	South Africa (2022)	Spain (2002)	United Kingdom (2022)	United States (2020)
Aluminium	5	●		●	●	●										●
Boron	1										●					
Brass	0															
Cadmium	0															
Carbon fibre	1										●					
Chromium	8	●			●	●			●	●	●		●			●
Cobalt	10	●		●	●	●		●	●		●		●		●	●
Copper	7			●	●	●	●		●				●	●		
Dysprosium (REE)	10	●		●	●	●		●		●	●		●		●	
Gallium	6	●			●			●			●				●	●
Graphite	8	●		●	●	●		●		●					●	●
Iron	6			●		●	●		●				●	●		
Lithium	12	●	●	●	●	●		●	●		●	●	●		●	●
Manganese	9	●		●	●				●		●		●	●	●	●
Molybdenum	4			●	●	●					●					
Neodymium (REE)	10	●		●	●	●		●		●	●		●		●	
Nickel	9			●	●	●			●		●		●	●	●	●
Phosphorus	6			●		●	●	●						●	●	
Praseodymium (REE)	10	●		●	●	●		●		●	●		●		●	
Selenium	1										●					
Silicon	6	●		●				●		●	●				●	
Silver	2								●					●		
Tellerium	4				●						●				●	●
Terbium (REE)	10	●		●	●	●		●		●	●		●		●	
Titanium	7	●		●	●			●	●		●					●

Note: REE = rare earth element

Source: *IEA. See endnote 47 for this chapter.*

CRITICAL MATERIALS OF RENEWABLE ENERGY, BY TECHNOLOGY

BIOENERGY

Bioenergy is the energy derived from organic materials, known as biomass. Biomass can be combusted to generate heat and/or electricity and can be converted to fuels for the generation of heat and power and for use in transport.[54] Biopower is a leading source of renewable electricity, contributing 10% of the global electricity supply in 2022.[55] In some scenarios, electricity generated from biopower is projected to increase three-fold by 2040, to reach 240 GW of total installed capacity.[56]

The material intensity of bioenergy boilers (excluding the fuel) is similar to that of their fossil counterparts. The designs of bioenergy boilers vary by energy source (e.g., biogas, biodiesel, wood chips or pellets), but all boiler types require the same materials, such as titanium and copper as well as steel and concrete.[57] (► **See Ecosystems chapter for discussion of the environmental benefits and potential impacts associated with bioenergy feedstocks.**)

Critical materials

Bioenergy boilers are the second largest user of titanium among energy technologies (after geothermal power).[58] Advantages of using titanium include improved heat conduction and protection against wrinkling caused by thermal changes or sudden exposure to a vacuum.[59] By 2040, the bioenergy sector is projected to account for an important share of titanium demand within the energy sector.[60]

Potential solutions to reduce critical materials use

Titanium is considered critical by six countries and the EU, and copper is recognised as critical by seven countries (► **see Table 5**). Given the capacities of titanium and copper to retain mechanical and chemical characteristics over multiple cycles of use, both metals are classified as highly recyclable materials, with recycling potentials of 80% and 95-100%, respectively.[61] Higher recycling rates can be considered a strategic avenue to address mineral criticality for the bioenergy sector. (► **See the Circularity section for more on circular solutions.**)

✓

Titanium and copper – used in bioenergy boilers – are considered highly recyclable materials.


Sandakan Sabah Seguntor

GEOTHERMAL ENERGY

Geothermal energy is derived from thermal and pressure differentials in the Earth's crust, providing direct thermal energy or electricity by use of steam turbines.[62] The globally installed capacity of geothermal power totalled around 14.6 GW in 2022 and is expected to quadruple by 2040.[63] Because of the corrosive nature of geothermal waters, geothermal power production requires the use of turbines and pipes made from a unique steel composite high in chromium, molybdenum, nickel and titanium. (► See Ecosystems chapter for more on geothermal energy.)

Critical materials

In descending order of criticality within minerals of geothermal energy, nickel is considered critical by nine countries, chromium by eight countries, titanium by six countries and the EU, and molybdenum by four countries (► see Table 5).[64]

Potential solutions to reduce critical materials use

All four of the critical minerals of geothermal energy have high potential for recycling. Both nickel and molybdenum are fully recyclable.[65] Chromium and titanium are estimated to be recyclable at 87% and 80%, respectively.[66] These high potentials present a favourable opportunity for investments in recycling initiatives.

In addition, geothermal aquifers offer promising potential for mineral recovery, with the ability to extract minerals such as aluminium, lithium and manganese. By one estimate, the mineral concentrations found in geothermal aquifers in the United States alone are sufficient to meet 60% of the world's demand for lithium as of 2021.[67] (► For more on the recovery of minerals from aqueous sources, see the Alternative Extraction Methods section.)

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HYDROPOWER

Hydropower is the largest source of renewable electricity globally. In 2022, the total installed capacity was around 1,220 GW, and hydropower generated an estimated 4,429 TWh of electricity.[68] Hydropower infrastructure relies heavily on cement and concrete (as well as steel for the turbines), and its mineral requirements are the lowest among renewable energy sources. As of 2010, the mineral requirements per megawatt for hydropower infrastructure were an estimated 1,050 kilograms of copper, 500 to 2,500 kilograms of chromium, 200 kilograms of manganese and 30 kilograms of nickel.[69] (► See Ecosystems chapter for more on hydropower.)

Critical materials

Chromium is deemed critical by eight countries, and copper by seven countries.[70] Compared to other technologies, hydropower requires very low quantities of these minerals, and future demand is not expected to increase significantly.[71]

Potential solutions to reduce critical materials use

Both chromium and copper are considered highly recyclable, with recyclability potential of 87% and 95-100%, respectively.[72] Research is also focused on reducing the use of chromium in hydropower turbines by replacing stainless steel with composite materials, which could bring further benefits such as reducing weight.[73] In addition, retrofitting ageing dams and hydropower plants can extend their lifespan and reduce the need for new construction, resulting in material and energy savings.[74]

SOLAR PHOTOVOLTAICS (PV)

The global solar PV capacity grew five-fold between 2015 and 2022 and is projected to increase a further 300-400% annually during the next two decades.[75] Solar PV systems comprise modules, inverters, trackers, mounting structures and general electrical components. The material intensities vary by module type. The most commonly used PV technology is crystalline silicon (c-Si), with a 95% market share in 2023.[76] Other technologies include cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si).[77] (► See Ecosystems chapter for more on solar PV.)

A typical c-Si module uses aluminium for the frame and glass for the casing; it also includes silicon (5%) for the solar cells, and copper (1%) and silver (less than 1%) for the interconnectors.[78] CdTe, CIGS and a-Si are thin-film technologies and are less mineral intensive than c-Si (although they require more glass). No silver or silicon is needed for CdTe and CIGS modules; instead, CdTe uses cadmium and tellurium, and CIGS uses gallium and selenium.[79] In addition to these alternative technologies to c-Si, innovations in manufacturing and design have greatly decreased the material use in PV modules. In 2021, designs of c-Si modules reflected a 50% reduction in the amount of silicon required per watt capacity and an 80% reduction in the amount of silver required per watt capacity compared to 2008.[80]


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✓ Beyond recycling, the repurposing and re-use of solar panels can reduce materials use.

c-Si technology is expected to continue to dominate the module market for the coming two decades.[81] The demand for copper to replace silver in solar cells and wiring is also expected to increase.[82] However, future demand for silicon and silver remains uncertain, as it depends heavily on the emergence of new solar energy technologies, including potential aerospace applications. For example, in 2022 the European Space Agency announced a plan to harness the sun's energy in space and transmit it back to Earth.[83]

Critical materials

Critical materials of solar PV energy systems include aluminium, copper, gallium, selenium, silicon, silver and tellurium. Notably, copper, silicon and gallium are considered the most critical, as they have received a high level of criticality designation by seven, six, and six countries, respectively (► see Table 5). Among these minerals, silicon[i] has the lowest re-usability rate.[84] Recycled silicon from solar panels poses challenges when attempting to re-use it in new solar cells, but it can be repurposed into new materials for other technological applications.[85]

Because solar PV technology is evolving rapidly, it is difficult to assess the future material demand. Emerging technologies that bring high theoretical efficiencies, such as gallium arsenide (GaAs) and Perovskite solar cells, might add two minerals deemed toxic – arsenic and lead – to the list of future materials demanded by solar PV cells.[86] On the other hand, the increase in the market shares of technologies such as CdTe and CIGS, and the emergence of additional PV technologies, might result in different opportunities and challenges.

Potential solutions to reduce critical materials use

Most critical materials in solar energy systems, such as aluminium, copper, and silver, exhibit high levels of recyclability for re-use in the solar industry.[87] In addition to recycling, three core circular economy principles – redesign, renovate and re-use – offer solutions for reducing materials use in the solar PV sector (► see Circularity section).

CONCENTRATING SOLAR THERMAL POWER (CSP)

Global CSP capacity totalled around 6.3 GW in 2022.[88] After a surge in the early 2010s, the market slowed and even contracted in 2021.[89] Nevertheless, according to some scenarios, CSP capacity is expected to grow 40-fold between 2020 and 2040.[90] CSP technologies use mirrors or lenses to concentrate sunlight and convert it into high-temperature heat to drive traditional steam turbines or engines that generate electricity. Some of the same basic technologies also can be used in a variety of

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[i] Silicon is the second most abundant material in the Earth's crust, but it needs to be purified to reach the quality required for creating the photovoltaic effect. Producing PV-grade silicon is associated with high costs and greenhouse gas emissions, and global production was heavily dominated by China as of 2022, leading many countries to consider silicon a "critical" material. See endnote 84 for this chapter.


Matjaz Krivic / Climate Visuals Countdown

industrial applications that require low (below 150°C) to medium (150-400°C) process heat – such as water desalination, food processing, and chemical and mineral processing.

The most common CSP technologies for electricity generation are parabolic troughs and central towers. Parabolic troughs have traditionally captured the market.[91] However, central towers have higher efficiency and greater storage capacity and are expected to dominate CSP in the future.[92] (► See Ecosystems chapter for more on CSP.)

Materials used in CSP towers include steel and concrete for the tower, and mirrors to reflect the sunlight (heliostats). Steam turbine equipment includes stainless steels and contains 9-12% chromium, as well as molybdenum, manganese, nickel, vanadium and carbon.[93]

Parabolic troughs include multiple parabolic trough-shaped mirrors in parallel rows, which are aligned to enable them to track the sun daily from east to west and ensure that the solar energy is continuously focused on the receiver pipes.[94] Common reflective materials include specialised solar-grade glass mirrors with a reflective coating, using aluminium-based materials. Silver and aluminium have the best reflectance and are the most common coating materials used in the reflecting layers of CSP concentrators.[95]

Copper is used for wiring, pumps, electric motors and the generator.[96] Molten salts are used for heat storage as well as for heat transfer in central towers; in contrast, parabolic trough systems rely on synthetic oil that flows in stainless steel tubes.[97]

Critical materials and potential solutions to reduce their use

Very little information is available on the challenges associated with materials use in CSP systems.[98] Several of the materials used in CSP towers and parabolic troughs are categorised as critical: aluminium, chromium, manganese, molybdenum, nickel and silver. However, a recent survey on concentrating solar heat systems highlights that the criticality associated with the supply of mirrors and receivers relates mainly to the high geographic concentration of manufacturing, as only one large manufacturer outside of China supplies these components.[99] Further research is required to discuss challenges and potential solutions.

SOLAR THERMAL HEATING

The cumulative global installed capacity of solar thermal heating systems was an estimated 542 gigawatts-thermal in 2022.[100] Scenarios project that by 2050, all buildings with available roof space and sufficient solar insolation will be equipped with solar thermal collectors.[101] Such systems include either flat plate or evacuated tube collectors.[102]

A flat plate collector uses a metal surface (the absorber) to capture the sun's heat, has a transparent cover to enable the sunlight to reach the absorber and prevent heating loss, and includes a layer of insulation material to avoid heat loss. Typically, the absorber plate is made of copper or aluminium; the insulation layer comprises wood, foam or an insulated metal; and the cover is glass.[103]

For evacuated tube collectors, the components are evacuated glass tubes, aluminium fins and a heat pipe. Metal pipes, typically made of copper, carry the fluid (usually water, which may be blended with propylene glycol to prevent freezing), which transfers the heat from the absorber to its end-use destination, either to heat storage tanks or to a solar absorption chiller.[104]

Concentrating solar collectors are increasingly being developed for high-temperature applications, particularly for solar industrial heat plants.[105] The main components of concentrating solar collectors are mirrors and receivers, similar to those used in CSP plants.

Critical materials and potential solutions to reduce their use

As with CSP technologies, further research is required to assess the challenges related to critical materials used for solar thermal heating and their potential solutions. The issue of concentration of manufacturing also applies to concentrated solar collectors.

WIND POWER

Wind power technologies (wind turbines) harness the wind's kinetic energy to generate electricity or mechanical energy.[106] Wind power capacity more than tripled over the decade 2012-2022, and the total generating capacity (including onshore and offshore wind power) is expected to increase 10-fold between 2020 and 2050, according to some scenarios.[107] (► See Ecosystems chapter for more on wind power.)

The type and quantity of materials required for manufacturing wind turbines depend in part on the turbine type and size. The two main turbine technologies are gearbox and direct drive. Although gearbox machines accounted for 70% of the world's wind power capacity in 2021, the market share of direct-drive technologies has increased in recent years (particularly for offshore wind turbines).[108] Direct-drive turbines are lighter, less vulnerable to high wind speeds, and require less maintenance; however, they rely more heavily on rare earth elements.[109]

Critical materials

Several minerals used in wind turbines are deemed to be critical, and the issue of the availability of materials required to deploy wind energy capacities has attracted growing attention (► see Box 5).[110] Between 2011 and 2015, wind turbines accounted for around 2.5% of the global demand for rare earth elements, which include neodymium, praseodymium, dysprosium and terbium.[111] Rare earth elements are deemed critical by numerous countries and the EU (► see Table 5). Compared to gearbox machines, direct-drive turbines rely more heavily on rare earth elements, requiring around 240 kilograms per MW (versus 60 kilograms per MW for gearboxes).[112]

Turbine blades are made of composite materials, which are usually derived from glass or carbon fibre. Certain models use balsa wood for the core of the blades, and wood compounds such as wood epoxy are under development.[113] Although not considered critical, the complex composite materials of wind turbines blades make them difficult to recycle.[114] Moreover, the surge in demand for balsa wood in recent years triggered supply shortages and price increases, and intensified illegal logging and forest degradation in the Amazon region (► see Ecosystems chapter and Energy Justice chapter).[115]

> ✔ Solutions being developed to reduce materials use for wind power include re-use and recycling practices for all turbine components, including the blades.

Box 5. Material Projections for Wind Energy Deployment in the European Union

In 2022 Siemens Gamesa estimated the quantities of materials necessary to build out the wind power capacity required to meet the EU's decarbonisation targets for 2050. The calculations were based on two of the company's current turbine models (one onshore and one offshore). Assuming that wind energy would generate half of EU electricity by 2050, Siemens Gamesa calculated a total installed capacity of 1,300 GW in 2050, up from 255 GW in 2022, then multiplied the required materials per capacity by the amount of new capacity calculated. The results, by material, are provided in Figure 19.

FIGURE 19. Sample Calculation of Material Needs to Reach 1,300 GW of Installed Wind Power Capacity in the European Union

Material	**Quantity needed to reach 1,300 GW by 2050** (in million tonnes)	**Global production volume in 2021** (in million tonnes)	**Share of 2021 global prodution volume**
Steel	120	1,900	6%
Glass fibre	6.5	–	–
Carbon fibre	1.6	–	–
Copper	1.3	26	5%
Aluminium	0.8	68	1%
Rare earths	0.1	0.28	36%

Source *Siemens Gamesa. See endnote 110 for this chapter.*


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Potential solutions to reduce critical materials use

In response to the supply vulnerability of rare earth elements, the wind power industry is seeking to adopt smaller magnets in turbines. Another option is to replace permanent magnets entirely, by using high-temperature superconductor prototypes, which offers significant savings in turbine size, weight and minerals. However, evidence is still limited on the long-term performance and efficiency of high-temperature superconductors in wind turbines, as only one turbine (a 3.6 MW unit in Denmark) uses this technology today.[116]

To avoid the issues related to balsa wood, some manufacturers are using polymers such as polyethylene terephthalate (PET), which are both lightweight and strong.[117] Increasingly, circularity principles are being applied to the design of wind turbines, with a focus on improved energy efficiency to maximise the energy output per unit. Solutions being developed include re-use and recycling practices for all turbine components, including the blades (► see Circularity section).

ELECTRICITY NETWORKS

The integration of variable renewable energy sources, such as solar and wind power, into electricity grids depends on the availability of reliable and secure networks. Transmission and distribution networks typically are expanded to meet rising demand and to ensure reliability, and the rapid increase in wind and solar generation is accelerating that growth.[118]

Critical materials

The two key materials in today's electricity networks are copper and aluminium. Copper has been the main material used in power lines due to its performance advantages, but aluminium is 3 times lighter and 3.5 times cheaper and is often used for overhead lines.[119] In 2020, an estimated 5 million tonnes of copper and 9 million tonnes of aluminium were used to build electricity grids worldwide.[120] To support the grid connection of renewable technologies by 2040, copper use could increase by up to 10 million tonnes, and aluminium use by up to 16 million tonnes, according to IEA scenarios.[121]

The transition to smart grids, which involves integrating information technology networks with electricity networks and using digital technologies, sensors, and software, will require resources beyond copper and aluminium.[122] However, a lack of consolidated data makes it difficult to accurately estimate the future material demands of these technological advancements.

Potential solutions to reduce critical materials use

As discussed earlier, aluminium and copper are recyclable up to 100% without losing their properties, and recycling these metals is much less energy intensive than primary production.[123] In addition, researchers are exploring alternatives for electricity networks that could offer increased efficiency, such as the use of superconductors or graphene, although these technologies and materials are either at the pilot stage or not yet deployed at scale.[124]

ENERGY STORAGE

Pumped storage is the predominant form of utility-scale energy storage, totalling 175 GW in 2022 and accounting for most of the world's energy storage capacity.[125] Pumped storage involves using surplus electricity to pump water to a higher elevation and then releasing it to generate electricity when needed.[126]

Although pumped storage currently dominates total energy storage, battery storage capacity is increasing at a much faster rate. In 2022 alone, 11 GW of utility-scale battery storage capacity

Box 6. Lithium-ion Battery Technologies

The main advantage of lithium-ion batteries is their high energy density (currently around 90-260 watt-hours per kilogram, Wh/kg). Because they are lighter in weight and more compact in size, they are preferred in systems that have space limitations. Lithium-ion batteries consist of three primary components: the cathode, anode, and electrolyte (current collector), with the addition of a separator in the case of liquid electrolytes. The material requirements of batteries depend heavily on cathode and anode technologies.

The leading lithium-ion battery technologies are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminium oxide (NCA) and lithium nickel manganese cobalt oxide (NMC). These technologies differ in their energy densities and other features.

- **LCO batteries** have the highest energy density (150-190 Wh/kg) and are used mainly in portable electronics. However, they are thermally unstable and have a relatively shorter life cycle.
- **LMO batteries** have better thermal stability and a longer life cycle, but have lower energy densities (100-140 Wh/kg). Their key advantage is their cobalt-free structure. LMO batteries are used mainly in electric bikes and some commercial vehicles.
- **LFP batteries** are thermally stable even at high temperatures. They are lower in cost and higher in life span – lasting around 2,000 cycles compared to 1,000 to 1,500 cycles on average battery life. Because of their lower energy density, they are used mainly in stationary energy storage and heavy-duty vehicles. Recently, Chinese automakers and Volkswagen have shown interest in LFP batteries due to their cobalt- and nickel-free structure, which makes them safe, inexpensive and simple.
- **NCA batteries** have the highest energy range (200-250 Wh/kg) but the most expensive structure. As of 2022, Tesla was the only electric vehicle manufacturer using NCA batteries in power system back-up and load shifting.
- **NMC batteries** have the longest life cycle and have dominated markets for battery electric and plug-in hybrid electric vehicles since the early 2000s. Despite their material-intensive structures and lower energy densities (140-200 Wh/kg), NMC batteries have been preferred by manufacturers of both battery electric and plug-in hybrid electric vehicles.

Source: *See endnote 129 for this chapter.*

was added to global electricity networks.[127] Annual installations of battery storage capacity could reach an estimated 105 GW by 2040.[128]

The rapid growth in demand for storage capacity in the electricity sector, as well as for battery electric vehicles, has increased the overall demand for batteries. As of 2020, lithium-ion batteries accounted for 95% of utility-scale battery energy storage applications and for 100% of the batteries used in electric vehicles (► **see Box 6**).[129]

Critical materials

For battery storage technologies, the key critical materials include aluminium, cobalt, copper, graphite, lithium, manganese, nickel, phosphate and silicon.[130] As the transition to renewable energy and electric mobility accelerates, the pressure on the already stretched supply chains for these minerals will increase greatly. This surge in demand will likely challenge the capacity of existing mineral extraction and production systems, potentially leading to increased competition for these resources, as well as price volatility.[131]

Most of the projected growth in demand for critical minerals used for battery storage relates to electric vehicle batteries (► **see Figure 20 and Box 7**).[132] However, this growing demand must be put in perspective with other uses of batteries such as in smartphones and other connected devices.

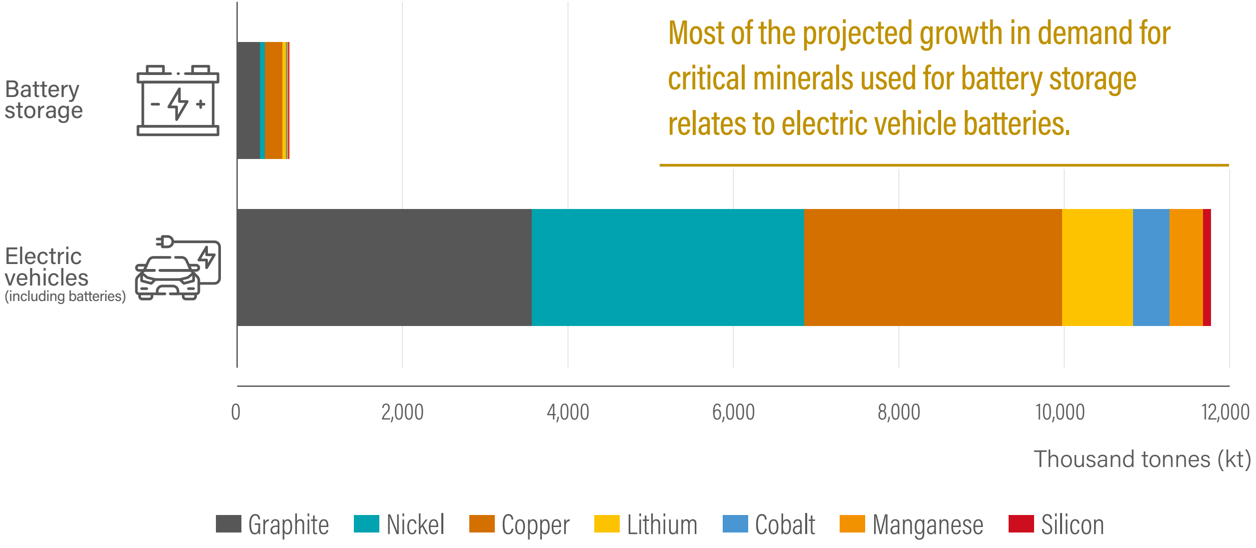
Potential solutions to reduce critical materials use

The energy storage industry is exploring ways to avoid or reduce the use of critical minerals as well as to recover and recycle them (► **see Circularity section**). Due to price vulnerabilities and concerns about the social impacts of mining, the amount of cobalt in batteries is expected to decline sharply over the coming decade.[133] Reduced use of cobalt is expected to increase the demand for nickel and manganese, which are considered competitive alternatives but are also deemed critical minerals.[134]

Alternatives to lithium-ion batteries are being designed but are not yet in wide use for electric vehicles or small-scale energy storage. Examples include iron-air batteries, lithium-sulphur batteries, sand batteries, sodium-ion batteries and solid-state batteries.

Iron-air batteries use iron as the anode and oxygen from the air as the cathode. They have the potential for high energy density and are made from abundant materials.[135] Lithium-sulphur batteries use a lithium anode and a sulphur cathode and have the potential to be lighter and less expensive.[136] Sand batteries use sand, an abundant material, as the anode.[137] Sodium-ion batteries use a sodium anode and a cathode made from materials such as iron, copper or manganese. They offer advantages such as low cost and easier recycling options compared to lithium-ion batteries.[138] Zinc-based batteries use zinc as the anode and cathode materials and are made from abundant materials with low toxicity.[139]

FIGURE 20. Projected Demand for Selected Minerals Used for Electric Vehicles and Battery Storage Under the International Energy Agency's Sustainable Development Scenario for 2040



Most of the projected growth in demand for critical minerals used for battery storage relates to electric vehicle batteries.

Source: *IEA. See endnote 132 for this chapter.*

Solid-state batteries use a solid electrolyte instead of a liquid one, which can increase the energy density and improve safety. With higher energy density and a longer cycle life, solid-state batteries show potential to surpass lithium-ion batteries in both performance and safety and to reduce weight and costs; however, their progression from laboratory to industrial scale remains uncertain.[140]

In addition to batteries and pumped storage, which are used to store electrical energy, other alternatives exist for storing energy in various forms, including thermal. Thermal energy storage involves storing heat energy in materials such as water or molten salts. The stored heat (or ice) can be produced from renewable thermal sources or from electricity. Although thermal energy storage is used mainly for storing heat (e.g., for industry, district heating and cooling, water heating and climate control in buildings, and cold chain logistics), it also can be used to produce electricity in conjunction with CSP plants[i].[141] Thermal energy can be stored for long periods of time, but for utility-scale uses this requires large storage tanks or spaces.[142]


JCT 600

Box 7. Electric Vehicle Battery Storage

The adoption of electric vehicles enables greater use of renewable electricity in the transport sector, thereby increasing the amount and share of renewables in transport. Large fleets of electric vehicles also offer the potential to increase flexibility in the electricity system, to the extent that the vehicle batteries are charged when surplus electricity is available (through demand management and incentive structures), with the potential to later feed the electricity back to the grid when demand exceeds production. This would ease the integration of ever-higher shares of variable solar and wind power into the grid.

In 2020, worldwide electric vehicle sales grew 40% – with nearly 3 million units sold – to reach a global market share of 4%. By 2022, the market share surged to 25%, with more than 10 million vehicles sold. Policy support is the primary driver of rising electric vehicle sales. As of January 2023, 54 countries had in place policy incentives for electric vehicles and targets for zero-emission vehicles. By 2050, between 70% and 100% of all new vehicle sales are expected to be electric.

Minerals are essential not only for electric vehicle batteries, but also for producing electric motors. The two mainstream electric motor technologies are permanent magnet synchronous motors and asynchronous induction motors.[143] Permanent magnet motors are more efficient and dominate the market, but they are mineral-intensive and expensive because they depend highly on rare earth elements (such as neodymium) as well as copper, iron and boron.[144] In contrast, induction motors do not require rare earth elements and are lower in cost, but they are less efficient and have higher copper requirements.[145] Already, companies such as BMW, Nissan, Renault, Tesla, Toyota and Volkswagen have announced steps to adopt more-efficient induction motor technologies – thereby eliminating the need for rare earth magnets.

Source: *See endnote 132 for this chapter.*


Ivan Radic

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[i] CSP facilities with thermal storage can inexpensively store the solar energy that they collect and use it to generate electricity reliably even when the sun is no longer shining.

CIRCULARITY

Enhancing circularity in the renewable energy value chain can facilitate the transition to renewables and help to overcome the negative impacts of extractive activities and end-of-life waste. Circular economies aim to use fewer resources to meet societal needs and to regenerate natural resources for the benefit of businesses, communities and the environment. Smarter product design and better processes can reduce waste by using products and services more efficiently and keeping materials in use for longer.[146]

A circular economy minimises waste and focuses on the product life cycle, targeting sustainable consumption (including re-use) of resources. In contrast, the traditional linear economy does not consider the environmental and social costs of production, and raw materials are collected and transformed into products that are eventually discarded as waste.[147] In a circular economy, products are made to last longer, communities share resources and save money, and energy is used more efficiently. Businesses maintain, re-use, remanufacture and recycle materials to create value for present and future generations.[148]

Organisations and scholars conceptualise varying sets of principles for circularity, although they converge on the aim of eliminating waste and pollution, (re)-circulating products and materials, and regenerating nature.[149] Seven key pillars of the circular economy can be applied to renewable energy technologies:

- **Redesign** involves (re-)designing products to have longer lifespans; to be manufactured from renewable materials to the extent possible, with minimal use of non-renewable materials (particularly critical minerals); and to allow for ease of repair, re-use and recycling.

- **Reduce** involves reducing the dependence on a specific product, such as by sharing products and services. It involves using efficient production processes and designing products that use less material to reduce overall consumption.

- **Repair and renovate** involve extending the lives of existing products and infrastructure through regular maintenance, repairs and upgrading or retrofitting to keep them in use for longer.

- **Re-use** is about using products more than once before they reach the end of their life.

- **Recover** is about extracting valuable materials and energy from waste, using "waste" from one industrial process as input for a new product cycle

- **Recycle** is about processing used materials and products into new ones.

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These seven principles can be applied to different phases of the life cycle of renewable energy technologies. Although overlaps may exist among categories, in broad terms redesign and reduce apply to the design and manufacturing phases; renovate, repair and re-use apply to the use phase; and recover and recycle apply to the end of life of technologies. It is important to focus on the entire life cycle of renewable technologies, applying all seven principles to ensure the maximum circularity for minerals.

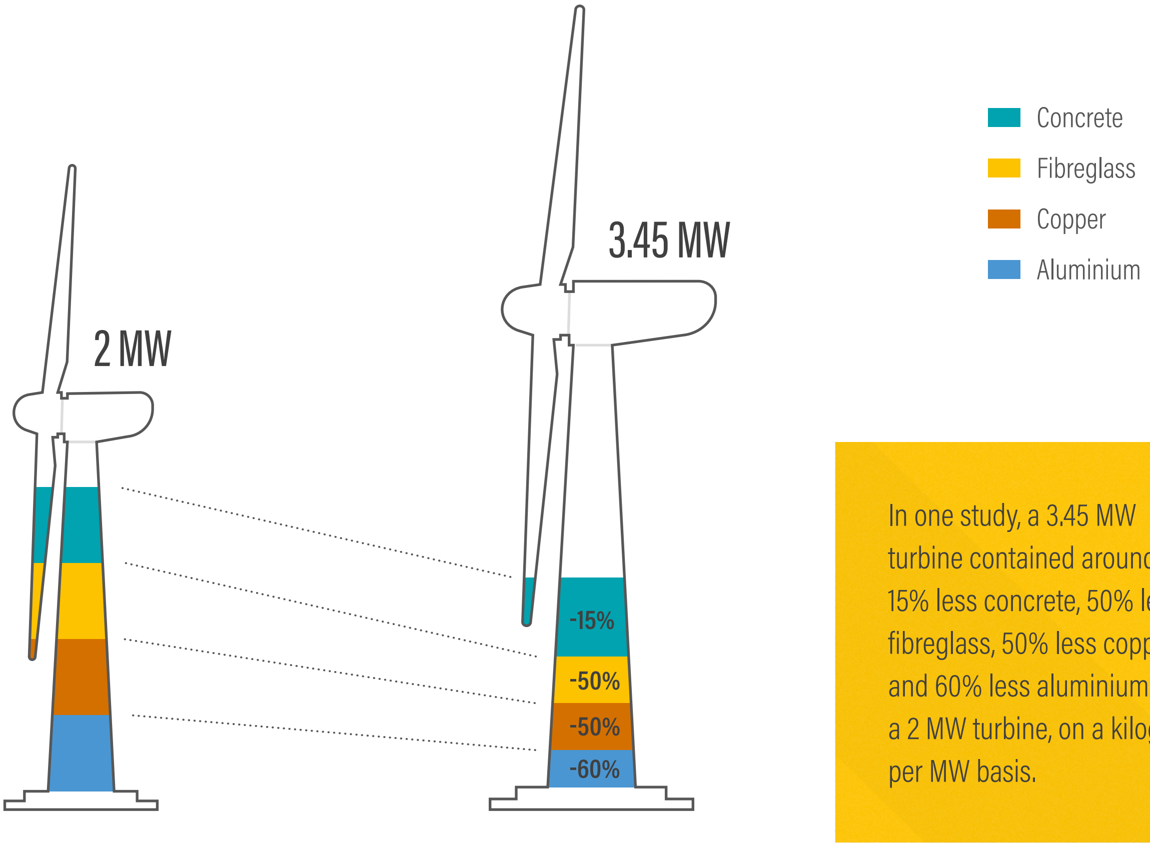
CIRCULARITY IN DESIGN AND MANUFACTURING (UPSTREAM): REDESIGN AND REDUCE

The principles of redesign and reduce aim to decrease the mineral demand per unit of energy produced through the redesign of renewable energy technologies. This allows for: 1) the use of fewer and reduced quantities of minerals per unit, 2) the use of minerals with higher recycling potential, 3) the use of minerals with less impact on society and the environment, including fewer emissions of toxic substances and greenhouse gases, less water use, less waste, no forced or child labour, and ethical work conditions, 4) increased mineral recycling rates, and 5) longer life cycles.[150]

In the wind energy industry, the growing size of turbines has crucially contributed to both the increase in capacity factor and the reduction in material use (► **see Figure 21**).[151] Taller towers, larger rotors and lighter drivetrains of newly commissioned onshore wind power projects have enabled higher average capacity factors globally, rising from 27% in 2010 to 34% in 2018.[152] Such advances have reduced the intensity of some materials in wind turbines. A study comparing turbines from the same manufacturer found that a 3.45 MW turbine contains around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine, on a kilogram per MW basis.[153] At the design stage, the wind energy industry is increasingly exploring materials and processes that allow for easier disassembly, recovery and recycling of turbine blades (► **see Box 8**).[154]

For solar PV, innovations in manufacturing and the redesign of c-Si panels have led to large reductions in material intensity (► **see Figure 22**).[155] Between 2008 and 2021, the amount of silver required per watt capacity fell 80% thanks to more efficient and less silver-intensive metallisation pastes, and the amount of silicon required per watt capacity has fallen by more than half due to the substantial reductions in wafer thickness.[156]

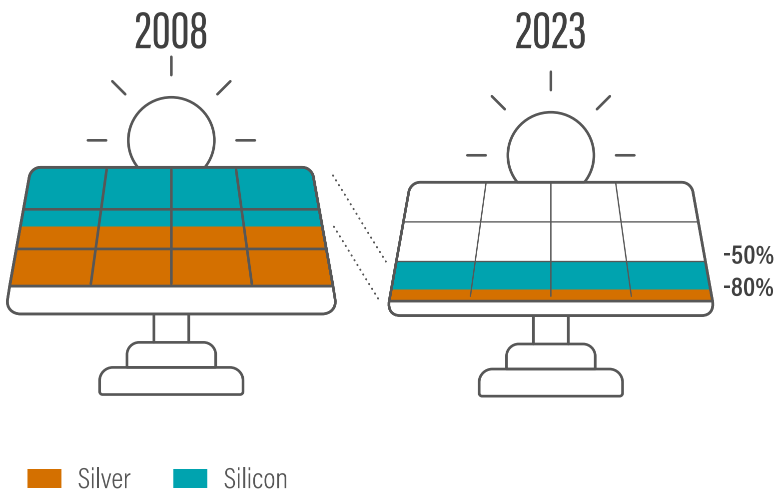
FIGURE 21. Decrease in the Material Intensity of Wind Turbines Due to Increased Capacity



Source: *based on A. Elia, M. Taylor and B. Ó'Gallachóir, 2020. See endnote 151 for this chapter.*

In one study, a 3.45 MW turbine contained around 15% less concrete, 50% less fibreglass, 50% less copper and 60% less aluminium than a 2 MW turbine, on a kilogram per MW basis.

FIGURE 22. Decrease in the Material Intensity of Solar Panels Due to Increased Efficiency



Since 2008, the amount of silicon required per watt capacity has more than halved due to the substantial reductions in wafer thickness, and the amount of silver required per watt capacity fell by 80% thanks to more efficient and less silver-intensive metallisation pastes.

Source: *based on ITRPV. See endnote 155 for this chapter.*

Box 8. Initiatives to Repurpose and Recycle Wind Turbine Blades

The wind manufacturing industry has focused increasingly on end-of-life challenges for turbine blades as it seeks to increase circularity. Several technological advances have emerged in recent years including the re-use or recycling of blades made from traditional materials and the development of more-sustainable blade materials.

- The Danish company Vestas has announced a collaboration with Aarhus University, the Danish Technological Institute and Olin to use a chemical process to break down epoxy resin into virgin materials, allowing old epoxy-based blades to be re-used for new ones.
- The Swedish energy company Vattenfall has set a target to recycle all dismantled wind turbine blades by 2030, with the first batch from the Irene Vorrink Wind Farm in the Netherlands to be turned into skis, snowboards and construction materials for solar farms. Due to the complex structure of turbine blades, Vattenfall is exploring collaboration with different companies to find the most suitable recycling solution.
- In 2021-2022, the Spanish-German company Siemens Gamesa launched commercially viable and recyclable onshore and offshore wind turbines using its RecyclableBlade technology. The company has set an ambitious target of producing 100% recyclable turbines by 2040. RecyclableBlade uses a resin that allows for more efficient material separation at the decommissioning phase. At the end of the blade's life, a mild acidic solution separates the resin from the recyclable materials (i.e., fibreglass, plastic, wood and metals), which can then be prepared for secondary use in sectors such as the automotive industry or consumer goods.

Source: *See endnote 154 for this chapter.*

Besides efficiency of scale, product redesign includes exploring ways to use sustainable materials in manufacture, make the product easier to repair to extend its lifetime, and make it easier to disassemble and recycle at end-of-life. For solar PV, research focuses on designing products with extended lifetime, with some results showing the possibility to extend the life of modules to up to 40 years and of inverters to up to 18 years.[157]

The use of bio-sourced materials in the design of renewable energy technology components is gaining attention. The EU-funded research project Pilatus, focused on designing solar panels for circularity, is exploring the use of bio-sourced and recycled materials in the encapsulants.[158] Several manufacturers also are seeking to reduce the use of rare earth elements in the permanent magnets used in some types of wind turbines. The goal is either to use more efficient manufacturing processes to produce permanent magnets with lower rare earth content per machine (but similar performance), or to substitute permanent magnet systems with systems that do not use rare earth elements.[159]

For battery storage, several pathways exist to reduce the use of critical minerals. As highlighted earlier, electric vehicle and storage battery technologies with reduced mineral intensities include cobalt-free lithium-ion batteries, iron-air batteries, lithium-sulphur batteries, pumped storage, sand batteries, sodium-ion batteries, solid-state batteries, super capacitor, thermal storage and zinc-based batteries. Manufacturers are investing not only in new battery technologies but also in technologies for recycling and re-using minerals from existing batteries.[160]

Initiatives have emerged to support the re-use or recycling of blades made from traditional materials and the development of new and more sustainable blade materials.

Siemans Gamesa

Shared electric mobility, public transport and active mobility (biking and walking) all contribute to reducing the need for electric vehicle batteries (and for the overall materials used in individual cars), thereby reducing material demand. Such solutions entail redesigning transport policies and infrastructure to allow for a shift away from individual cars, and are increasingly being considered by policy makers.[161]

CIRCULARITY IN THE USE OF RENEWABLES (OPERATIONS): RENOVATE, REPAIR AND RE-USE

To promote circularity in renewable energy technologies, it is crucial to apply principles of renovate, repair and re-use to extend technology lifetimes and reduce the demand for new resources. For example, retrofitting hydropower plants can extend the life of the infrastructure while increasing energy efficiency through the installation of new and more-efficient turbines.[162] Siemens Gamesa has proposed a life extension programme that would target a lifetime of 30 years for its wind turbines.[163]

Similarly, refurbishing wind turbine components to extend their service life can avoid the need for complete replacement, thereby reducing the use of materials and carbon emissions while creating local and highly skilled jobs. Vestas estimates that re-winding the copper of wind turbine generators can save up to 70% of materials and avoid 45% of CO_2 emissions compared to replacing the units with new generators.[i,164]

However, the rapid evolution of technologies towards greater efficiency, combined with cost declines, may incentivise project developers to repower installations rather than seeking to extend their lifetime.[165] Repowering involves the dismantling of old equipment, such as wind turbines or solar panels, and installing completely new equipment at existing sites. Although repowering does not reduce the use of materials, it can offer advantages such as increased energy generation with no additional environmental impact on the site of operations.[166] When considering end-of-life options for installations, the benefits and environmental impacts of different solutions may be assessed on a case-by-case basis.[167]

Repurposing parts from demounted units that still have some life left is an example of the re-use principle. Firms are increasngly focusing on reselling used components from wind and solar systems, including cables, gearboxes, generators, blades, transformers, solar panels, inverters and storage units.[168]

Retired electric vehicle batteries are being repurposed as residential, commercial and utility-scale energy storage units. Because these batteries typically have terawatt-hours of unused energy and maintain up to 80% of their usable capacity, automakers have initiated trials to re-use them for "second life" applications.[169] In January 2020, Nissan and American Electric Power launched a pilot study in the US state of Ohio to test the stationary storage characteristics of expired Nissan Leaf batteries.[170] Similarly, BMW

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[i] An additional advantage of refurbishing existing facilities instead of constructing new ones is the possibility to leverage on the existing installations, such as wind turbine towers, and keep the existing legal agreements, like operating permits. See endnote 164 for this chapter.

> Companies are increasingly focusing on reselling used components from wind and solar systems, including cables, gearboxes, generators, blades, transformers, solar panels, inverters and storage units.

introduced a plan to re-use batteries from its i3 electric vehicle model in stationary storage products to support peak load reduction and provide back-up power for homes.[171]

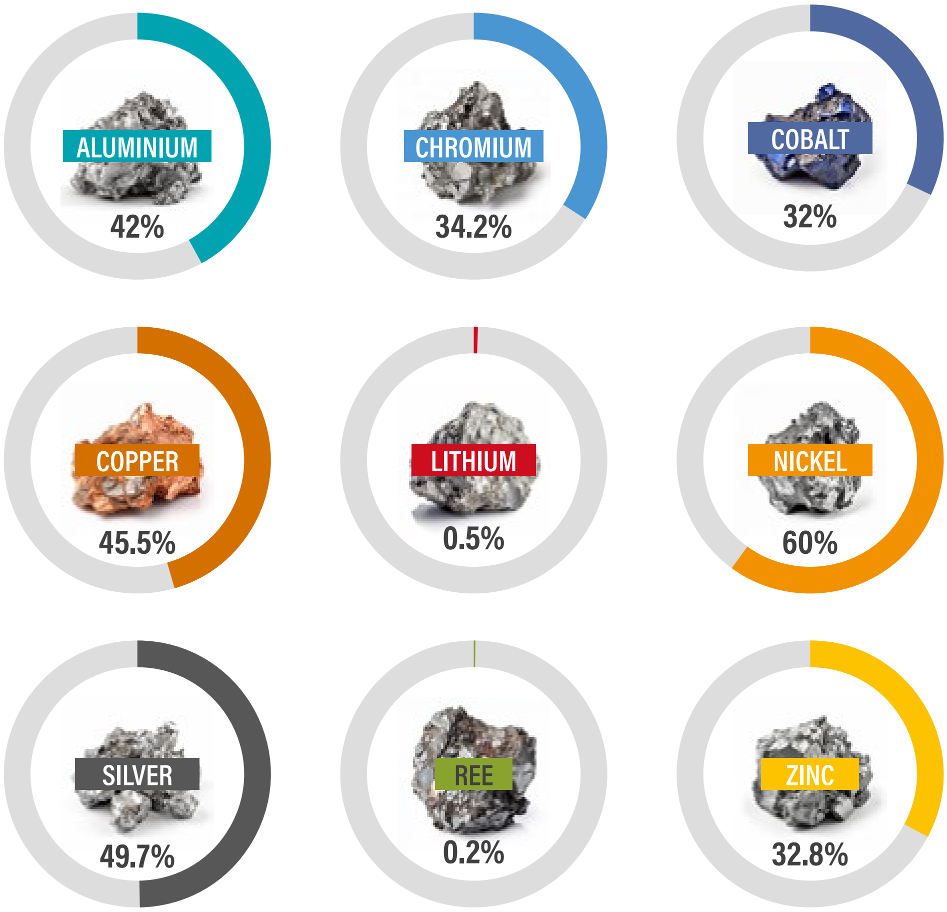
CIRCULARITY AT THE END OF LIFE (DOWNSTREAM): RECOVER AND RECYCLE

Circularity at the end-of-life of renewables refers to the processes of recovering components at the end of their useful life and recycling their materials. The recyclability of critical minerals varies depending on the specific mineral and the technology used to extract it (► see Figure 23).[172] Some critical minerals, such as aluminium, copper, and nickel, have high recycling rates due to their economic value and the efficiency of existing recycling technologies. Others, such as rare earth elements, are more difficult to recycle due to their low concentrations in products and the complexity of the extraction and separation processes.[173] Research suggests that for solar panels and wind turbines, up to 90% and 95%, respectively, of the components can be recycled, and up to 100% for batteries.[174]

Lithium, a key component in batteries, is highly recyclable without losing its properties. The US-based company Redwood Materials claims to have the ability to recycle as much as 95% of the metals used in lithium-ion batteries.[175] As of 2022, only an estimated 5% of lithium-ion batteries were being recycled globally, although the share will likely rise as countries adopt policies to increase recycling.[176]

A notable US private recycling initiative, Nth Cycle, focuses on recovering critical minerals required for the energy transition from end-of-life sources such as batteries, nickel scrap, e-waste and other forms of mineral scrap and waste.[177] The company currently recovers cobalt, nickel, and copper and plans to expand to recover vanadium and platinum group metals from industrial waste and tailings.[178] Despite the potential of such practices, recovery

FIGURE 23. Recycling Rates of Selected Materials Used in the Energy Transition, 2021



> Many recovery and recycling technologies are available. There is a need for a favourable policy environment for their development at scale.

Note: REE = rare earth elements.

Source: *IEA and Copper Alliance. See endnote 172 for this chapter.*


Alaska Center for Energy and Power

technologies remain costly. Nth Cycle is funded by government grants, state government programmes, and private venture capital, and is seeking further funding through domestic content bonuses, critical minerals processing tax credits and investment tax credits.[179]

In the solar PV industry, First Solar, a major player in the thin film global market, has announced recycling rates of 90% for its panels, including closed-loop recovery of the semiconductors used in new panels.[180] The company has recycling facilities in Germany, Malaysia, the United States, and Viet Nam, and has proposed a module collection and recycling service based on a pay-as-you-go model.[181]

Similarly, the US company SolarCycle was founded in 2022 to address the challenges of creating a circular economy for solar energy infrastructure and equipment. The company's experts in solar technology, recycling and sustainability have developed a patented technology and a scalable business model that can cost-effectively extract 95% of valuable materials from retired solar panels and return them to the solar supply chain.[182] SolarCycle's proprietary technology enables it to remove metals such as silver, silicon, copper and aluminium from retired panels and to recycle or repurpose panels currently in use.[183]

In 2016, the US Solar Energy Industries Association launched a National PV Recycling Program in the United States. The programme involves a network of recycling and refurbishment providers offering end-of-life management services to solar and storage installers, project and system owners, developers, distributors and other parties.[184]

Similar examples of recycling have emerged in the wind industry for the recycling of retired wind turbine blades (► see Box 8).[185]

CHALLENGES TO CIRCULARITY

At the design stage, the challenges to circularity may be of a technical nature, but economic considerations also have an impact on design decisions.[186]

In the solar PV industry, the technical challenges for recycling solar c-Si PV modules are related less to the specific materials used than to the complexity of breaking down the panels for proper recycling. Experts suggest that the current design of PV panels can make it difficult to separate the semiconductors from the back sheet and glass layers and highlight the need to redesign structures for recycling, including by using less adhesive to simplify the separation process.[187]

When designing products, a trade-off may exist between making them easy to disassemble for recycling and ensuring that they have a long lifetime, as easy disassembly can sometimes compromise a product's strength. The profitability of recycling materials also must be considered. For example, frameless solar PV panels are lighter and easier to disassemble but are more fragile, whereas framed panels are harder to disassemble but contain aluminium, which is of value and can be recycled.[188]

Stakeholders highlight that there is a need to create markets and regulatory frameworks for materials at their end of life, which will in turn incentivise the design of more circular devices.[189] Regulations, standards, economic incentives and a skilled workforce are all needed to drive the market forward.[190]

In Europe, the **re-use, repair and refurbishment** of PV modules remains mostly informal, carried out by independent private companies and not always involving the original manufacturers.[191] Regulations and standards for testing, certifying and labelling of refurbished PV modules remain limited, and in many cases repaired or refurbished solar PV modules are sold to less developed markets.[192]

Furthermore, the lack of regulatory frameworks and standardised reliability testing – including safety and performance guarantees for re-used or repaired products – hinders consumers' trust in such products and may orient their choices to new ones.[193]

Repairing and maintaining renewable energy equipment, as well as ensuring confidence in the reliability of refurbished equipment, requires skilled technicians; however, recruitment difficulties are reported in both the solar PV and wind industries.[194]

When it comes to **recycling the components** of renewable energy technologies and recovering the minerals, some of the challenges can arise from the design of the products. Moreover, although many recovery and recycling technologies are available, the lack of financial incentives and a favourable policy environment can hinder their development at scale.[195] While disassembling solar panels still faces technical challenges, experts also highlight that current recycling technologies for c-Si modules (which account for around 90% of the global market) do not generate enough revenue from recovered materials to offset the cost of the recycling process.[196] While recycling processes easily recover aluminium, copper, and glass, other materials such as silver, silicon, and lead, which make up most of the potential value of c-Si modules, are currently barely recovered.[197]

In many countries, the cost of recycling remains higher than that of disposal. According to the National Renewable Energy Laboratory (NREL), recycling solar PV modules in the United States ranges from USD 15 to USD 45 per module, whereas disposal can cost less than USD 1 per module at a non-hazardous waste landfill and less than USD 5 per module at a hazardous waste landfill.[198]

For wind turbines, the industry is developing technical solutions to recycle the blades (► see Box 8), but other considerations such as the cost of transport to recycling facilities can hinder the economic viability of these processes.[199]


Rwanda Green Fund

POTENTIAL SOLUTIONS FOR INCREASING CIRCULARITY IN RENEWABLE ENERGY

Research and development plays a critical role in the design stage of more easily re-used, repurposed and recycled equipment.[200] Design solutions to improve end-of-life circularity are being explored through both public and industry-led research programmes. NREL and the IEA Technology Collaboration Programme are leading significant research on solar PV circularity.[201] In Europe, the EU Joint Research Centre and EU-funded projects such as MAREWIND, MODVION and REFIBER are studying potential technological solutions, as well as enablers and barriers, to promoting circularity across renewable energy technologies.[202]

An example of the extensive ongoing research in the wind industry is the DecomBlades project in Denmark, which involves several wind energy and recycling companies, as well as universities and industrial research organisations, and is investigating technological options for recycling wind turbine blades.[203] (► For more on blade recycling, see Box 8.)

Enabling policies and economic opportunities for re-use, repair and recycling services and business models are also key for incentivising the research on design for circularity.[204] Policies can mandate or provide incentives for repairing renewable energy assets during operation and repurposing, recovering and recycling them at their end of life.[205]

> Policies can mandate or provide incentives for repairing renewable energy assets during operation, and for repurposing, recovering and recycling them at their end of life.

For example, the EU's Waste Electrical and Electronic Equipment (WEEE) Directive introduced extended producer responsibility for solar PV modules, requiring panel manufacturers to ensure the take-back and recycling of their products within the EU, including the associated administration, reporting and funding.[206] Within the WEEE context, in France the Producer Responsibility Organization (PRO) SOREN is mandated by French authorities to collect and manage used solar panels. SOREN has partnered with the social enterprise ENVIE 2E Aquitaine to develop a second-hand market stream for solar panels, including quality guarantees in regard to security, lifetime and performance.[207]

The US state of Washington has enacted legislation that requires manufacturers of solar modules to provide the public with a convenient and environmentally sound way to recycle the modules at no cost to the owner.[208] The companies are required to submit stewardship plans, which must include a target for the rate of combined re-use and recycling of collected solar PV modules based on a percentage of the total weight of modules collected (with a minimum share of 85%).[209] In Japan, facilities of 10 kW or larger, installed under the feed-in tariff system, are required to pay into a decommissioning fund for 10 years.[210]

When it comes to extending the life of wind turbines, industry stakeholders argue that revenue stabilisation mechanisms for lifetime extension projects could ensure their viability compared to decommissioning. For example, the value of the extended lifetime of the wind turbine to the electricity system could be reflected in public support schemes.[211]

Public procurement can lead the way for a viable market of repair and re-use. For example, renewable energy auctions can include non-price criteria such as the availability of spare parts for repairing products or a percentage of re-used materials in new projects.[212] In general, public subsidies, grants or tax incentives can be used to support businesses providing repair, re-use and recycling and can also encourage private investment by reducing investment risk.[213]

More broadly, bans on the landfilling of electronic waste can increase the availability of materials and the economic viability of recycling.[214] Examples include e-waste landfill bans in Western Australia and South Africa.[215]

Independent or third-party **certification standards** that provide assurance on the safety, efficiency and durability of repurposed solar PV modules have the potential to enhance the resale value and to elevate consumers' perceptions of the quality of repurposed products. This can increase their confidence in circular solutions.[216] The EU-funded project CIRCUSOL aims to formalise the re-use, repair and refurbishment value chains within the PV industry. It will bring together players in the solar PV supply chain to prepare for the first-ever extension of certification and labelling to second-life modules. The protocols will encompass aspects of safety, reliability and performance.[217]

Certification also provides a tool for traceability. The Cradle-to-Cradle global certification programme offers a comprehensive environmental evaluation based on a product's environmental and social impact throughout its life cycle, from raw material extraction to disposal or recycling. Developed in 2002, the programme has since been applied to a wide range of products.[218] For solar panels, cradle-to-cradle certification evaluates factors such as the environmental impact of the materials used in manufacturing, the energy and water use in manufacturing, and the recyclability of panels at the end of life.[219] The certification also considers the social impact of the manufacturing process, including worker safety and labour practices.

A skilled workforce is fundamental to the principles of renovate and re-use. The US Department of Energy has programmes to strengthen the human dimension of the renewable energy transition, such as creating a workforce equipped to operate, maintain, repair and renovate these systems.[220].

Certification schemes can also grant that the technicians have the level of skills required. However, these schemes may vary or might be inexistent in many countries, even though training for such qualification exists. In the EU, Directive 2009/28/EC establishes uniform requirements for technician accreditation.[221]

✓

Certification standards can provide assurance on the safety, efficiency and durability of repurposed solar PV modules.

Lance Cheung

EXTRACTION OF MINERALS

Most of the raw materials needed for the renewable energy transition currently come from mines. This is because of the limited availability of recycling infrastructure and the absence of value chains and regulatory support for recycled materials. These challenges urgently need to be addressed as the energy sector becomes a major player in mineral markets, with renewable technologies and battery storage the fastest growing segment.[222]

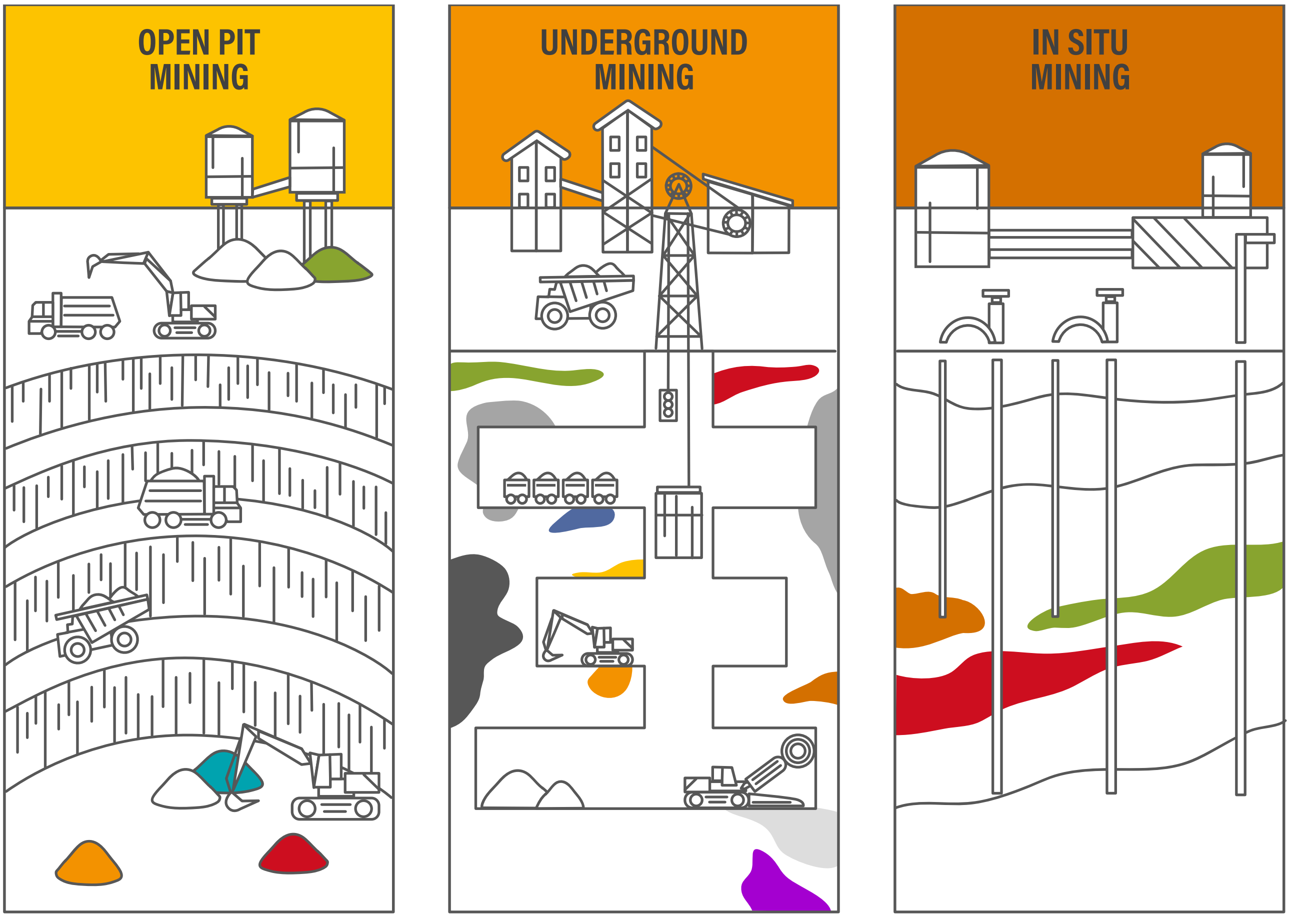
Even as the world transitions to a renewables-based energy system, it is crucial to consider the impact of the current supply chain on the environment and society. By understanding and addressing the numerous challenges facing the mining sector, as well as potential solutions, is possible to work towards a more sustainable and equitable renewable energy future.

CONVENTIONAL MINING PRACTICES

The minerals used in renewable energy technologies and battery storage rely mostly on conventional mining practices.[223] The main conventional methods used to extract these minerals are open-pit mining, underground mining and solution mining (► see Figure 24).[224]

Open-pit mining, also known as surface mining, is the most common method for extracting minerals and ores.[225] It involves removing the topsoil and overburdening it to reach the deposit. The minerals are then extracted by drilling and blasting the ore, and the resulting material is then transported to a processing plant. Open-pit mining is typically used for minerals found near the surface of the earth, such as aluminium, lithium, nickel and rare earth elements.[226]

FIGURE 24. Conventional Mining Methods Most Used for the Extraction of Critical Minerals



Source: *See endnote 224 for this chapter.*

Underground mining is typically used to extract minerals found deeper in the earth. It involves creating tunnels and shafts to access the deposit, and the minerals are extracted by drilling and blasting the ore. Critical minerals that can be extracted through underground mining include cobalt, copper, lead, lithium, nickel, palladium, platinum, silver, zinc and rare earth elements such as dysprosium, neodymium and praseodymium.[227]

Solution mining, also known as in-situ leaching, is a method of extracting minerals by dissolving them in a liquid solution. This technique is used to extract minerals found in underground salt deposits and in hot mineral springs. The dissolved minerals are recovered by evaporating the solution and collecting the minerals that remain. Solution mining is used to extract minerals such as copper, lithium, and several rare earth elements, including scandium, yttrium and cerium.[228]

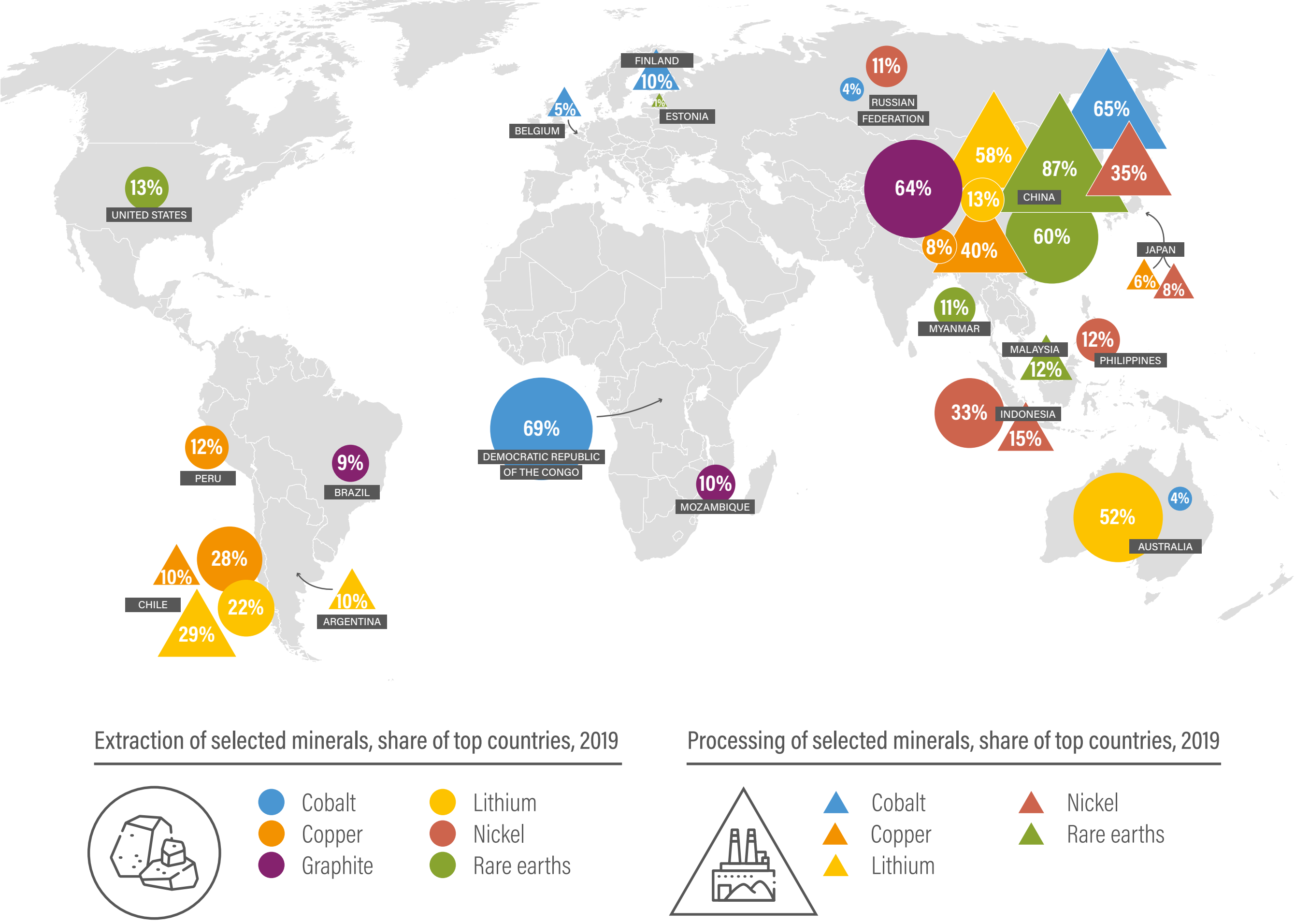
Leading Countries

Geographically, the mining of minerals used in renewable energy technologies and battery storage is highly concentrated (► see Figure 25).[229] This creates dependence on a few countries or regions for supply, which can lead to risks to the security of supply, market manipulation and geopolitical tensions.[230] For critical minerals such as cobalt, graphite, lithium, and rare earth elements, the top three producing countries control more than 75% of the global output.[231] Cobalt, graphite and lithium all play a vital role in determining the energy density, longevity and performance of modern battery technologies.[232]

An estimated 70% of global cobalt production takes place in the Democratic Republic of the Congo, followed by the Russian Federation and Australia (less than 5% each).[233] China produces nearly 65% of global graphite sources, followed by Mozambique (10%) and Brazil (less than 10%), and Australia produces 50% of the current lithium supply, followed by Chile (20%) and China (10%).[234] For rare earth elements, China is the major producer, with 60% of the global supply, followed by the United States (10%) and Myanmar (10%).[235]

Geographical concentration of copper and nickel production follows a similar pattern, with the top three countries producing around 50% of the global supply.[236] Around 30% of today's copper production takes place in Chile, followed by Peru (10%) and China (less than 10%).[237] Nickel is produced mainly in Indonesia (35%), the Philippines (10%) and the Russian Federation (10%).[238]

FIGURE 25. Leading Countries in the Mining of Selected Minerals Used for Renewable Technologies and Energy Storage



Source: *IEA. See endnote 229 for this chapter.*

CHALLENGES OF MINING

Environmental Impacts

Extracting minerals has impacts on air quality, water resources management and biodiversity.

Air quality

The primary source of air pollution from mining activities is particulate matter mobilised during excavations, blasting, ore crushing, transport of materials and wind erosion. Fugitive dust from tailings facilities, stockpiles, waste dumps and haul roads, as well as exhaust from trucks and other mobile sources, also contribute to particulate matter emissions. Air emissions from fuel combustion in stationary sources (such as drying and smelting operations) and in mobile sources, explosions and mineral processing contribute to air pollution as well.[239] Because of the potentially severe health impacts on people living near mining operations, it is essential to minimise these polluting emissions.

Water management

Extracting and producing minerals requires large amounts of water and poses risks of water contamination.[240] This is particularly challenging in regions where clean water sources are scarce, such as the "lithium triangle" of Argentina, Bolivia, and Chile, home to around 53% of the world's identified lithium resources.[241] The most long-lasting impacts of mining on water resources come from the wastewater generated. Acid mine drainage, which results from water flows encountering sulphide-rich materials, can persist long after a mine has closed. Tailings ponds used to store waste materials pose a risk of contamination to downstream water bodies, including potential damage from dam failure. Dewatering operations, which involve pumping out groundwater to maintain access to the mine site, can cause decreases in the water table or contaminate aquifers.[242]

Biodiversity loss

Mining activities can greatly impact biodiversity through the removal of vegetation and changing the composition of surface soil and riverbeds. The impacts of open-pit mines can span several kilometres. Alongside air emissions and water pollution, changes in land cover can lead to significant biodiversity loss. Few studies have focused specifically on the biodiversity impacts of mining minerals used for the renewable energy transition; however, research found that electricity generation overall accounted for 10% of global mining-related biodiversity loss in 2014.[243] The impact of coal-fired electricity on biodiversity loss was ten times higher than renewables per unit of electricity generated.[244] A recent US study revealed that surface coal mining leads to a 40% loss of aquatic biodiversity, with streams from heavily mined watersheds harbouring 40% fewer species than streams with cleaner water.[245]


Adobe Stock

> Independent assessment of mining practices is essential to ensure that minerals are responsibly sourced and that environmental impacts are minimised.

✔ Policies can ensure that Indigenous Peoples are included in decision-making processes related to planning, permitting, regulation, monitoring, and evaluating, and that the economic gains are shared with them.

Social Dimensions

Displacement of communities

The changes in land cover resulting from mining activities (especially expansive open-pit mines) can lead to the displacement of communities. Communities may be displaced in the project area where the mining activities occur, or due to the loss of local natural resources that residents depend on for their livelihoods. Displacement also may result from changes in environmental and social conditions, including increased pollution of land, air and water; disturbance and destruction of culturally significant sites; and the effects of labour migration to the area.[246] In total, global mining activities disturb an area covering between 0.3% and 1% of the Earth's land surface, suggesting that displacement due to mining is a widespread problem affecting many communities.[247]

Poor working conditions

Artisanal and small-scale mining (ASM) has increased greatly in recent years. ASM refers to mining by individuals, groups, families or co-operatives with minimal or no mechanisation, often in the informal sector. The main commodities in the ASM sector are reported to be gold, diamonds, tin, tantalum and cobalt.[248] The increase in ASM has led to poor working conditions – including forced labour, child labour, and a lack of safety equipment and training – for the estimated 40.5 million people engaged in this activity as of 2017 (an increase from 30 million in 2014, 13 million in 1999 and 6 million in 1993).[249] In contrast, around 7 million people worked in industrial mining in 2014.[250] In many mineral-rich countries, such as the Democratic Republic of the Congo and South Africa, some communities rely solely on ASM income.[251] Although data on ASM remain difficult to access, it is clear that more needs to be done to improve the sector's working conditions and safety standards.[252]

Impacts on Indigenous Peoples

Most of the world's mining projects for minerals related to the renewable energy transition are situated on or near Indigenous lands, directly impacting the lives and livelihoods of these communities.[253] In the lithium triangle of Argentina, Bolivia, and Chile, the main concerns affecting Indigenous land areas are water scarcity and air and water pollution.[254] Such concerns are crucial to consider when designing human rights-compatible permitting processes, as many Indigenous lands are protected by the UN Declaration on the Rights of Indigenous Peoples, which gives these communities explicit consultation and consent rights, such as mandatory Free, Prior and Informed Consent (FPIC) (► **see Energy Justice chapter**).[255]

Governance Dimensions

A related issue is the relationship between governance and the extraction of minerals. In resource-rich but economically unstable countries, mineral extraction is often associated with corruption, with the revenues frequently being misused rather than directed towards socio-economic development.[256] In many cases, these revenues are used to finance armed conflicts or for private gain.[257] This is also a challenge facing minerals extraction for renewables. Corruption can deprive citizens of the benefits of natural resources and undermine the rule of law, among other impacts. In addition, mining activities can lead to criminality, increased sexual violence and attacks against environmental defenders.[258] (► **See Energy Justice chapter for more on governance challenges of the energy transition.**)

ALTERNATIVE EXTRACTION TECHNIQUES

Urban Mining

Also known as e-waste mining, urban mining involves extracting valuable metals and minerals from electronic waste found in residential areas, including computers, phones and other devices. Currently, only around one-fifth of the estimated 50 million tonnes of e-waste produced annually is recycled.[259] In the EU, the recovery of certain minerals from e-waste increased between 2016 and 2020, including manganese (rising from 151 to 168 kilotonnes), graphite (from 40 to 71 kilotonnes), cobalt (from 22 to 26 kilotonnes), copper (from 34 to 60 kilotonnes) and lithium (from 9.3 to 17 kilotonnes).[260]

Urban mining has the potential to greatly reduce the energy used for mineral extraction. Research suggests that novel processes for extracting valuable metals from e-waste could use 500 times less energy than conventional methods for mining these materials.[261] Unrecycled e-waste severely damages the environment, as electronics contain toxic materials such as lead, zinc and flame retardants. E-waste can have harmful effects on air quality if combusted in waste facilities, and heavy metals can seep into the soil, neighbouring crops, groundwater and ecosystems.[262]

However, urban mining has its challenges. Legislation often falls short of incentivising proper e-waste management, data are lacking on the amount of extractable minerals, and it can be hard to plan for private investment in the face of uncertain policies and markets.[263] A key challenge to urban mining is the need for advanced technologies and technical knowledge, especially in developing countries.


Adobe Stock

Aqueous Recovery

Aqueous recovery of minerals entails extracting them from water sources, such as seawater, desalination brines, oil- and gas-produced waters, and acid mine drainage. A recent study highlights the potential to extract minerals such as lithium, strontium, magnesium and several rare earth elements from select geothermal sources in the United States, in quantities significant for the US supply.[264] The environmental impacts of aqueous recovery on water, air and land are much lower than for conventional mining.[265] Aqueous recovery eliminates the negative impacts of processed water waste on the environment.[266] Yet despite the method's promise for securing the minerals necessary for the renewable energy transition, it remains theoretical and has yet to be commercially tested.[267]

Phytomining

Phytomining (or agromining) is a method of extracting metals from plants via phytoextraction, which uses a group of plants called hyperaccumulators that have the ability to absorb and store large quantities of metals in their leaves, stems and roots.[268] Although the initial goal of phytoextraction was hazard mitigation, phytomining is emerging as a possible method for extracting minerals.[269] As with the recovery of minerals from water resources, however, it remains theoretical and lacks practice.

> ✓ Urban mining involves extracting valuable metals and minerals from electronic waste found in residential areas.

Bioleaching

Bioleaching uses microorganisms to extract metals from ores and other mineral sources. The microorganisms are added to a solution containing the metal-containing material; they then consume the minerals (such as cobalt, lithium and nickel) and convert them into a soluble extractable form. The resulting solution is processed to extract the minerals and metals. Bioleaching could be used to recover minerals from end-of-life products, such as e-waste or spent batteries, and convert them into usable materials. Bioleaching also can extract metals that are difficult or impossible to recover through traditional methods. Although bioleaching brings several advantages, including lower environmental impacts, energy use, and costs, it too remains theoretical and needs more practical testing.[270]

UNCONVENTIONAL EXTRACTION TECHNIQUES

As the demand for minerals increases and the impacts of conventional mining become more apparent, mining techniques such as deep sea mining and space mining are seen by some actors as potential options for the mineral supply. Despite not being able to fully replace conventional mining, these alternatives are being advanced as opportunities to overcome mineral supply bottlenecks; however, they do not address the fundamental issues of limited extraction capabilities and present a wide range of negative impacts.

Deep Sea Mining

Deep sea mineral reserves are potentially richer than land-based ones.[271] For example, in the Clarion-Clipperton Zone between Mexico and Hawaii, seabed metal nodules contain an estimated six times more cobalt and three times more nickel than the entire land-based reserves for these two minerals.[272] The International Seabed Authority controls all mineral-related activities on the seabed. As of January 2023, it had signed 31 fifteen-year contracts with 22 government agencies for the exploration of polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts, which are expected to include rich reserves of cobalt, copper, gold, iron, manganese, nickel, lead, platinum, silver, rare earth elements and zinc.[273]

Deep sea mining is a highly criticised technique in the quest for minerals because of its potentially large environmental effects, such as destroying seabed habitats and stirring up sediment clouds with toxic heavy metals.[274] Additionally, legal frameworks and property rights in the oceans are unclear, and uncertainty exists about the quantity of extractable minerals and their durability over time.[275] In light of the challenges, several countries and environmental organisations have argued for a precautionary approach (► see Special Focus 3) and called for a moratorium or full ban on deep sea mining activities.[276]

Space Mining

The idea of mining minerals in space is not new. Studies to understand the mineralogy of celestial objects date back to the US Apollo mission to the moon in the 1960s.[277] However, with technological advances and the increasing demand for minerals, space mining is becoming more of a reality, with interest in extracting rare earth elements as well as gold, iridium, iron, magnesium, nickel, palladium and platinum.[278]

The geopolitical competition to pursue space mining includes China, India, Japan, Luxembourg, the Russian Federation, the United Arab Emirates, the United States and the European Space Agency.[279] The US Space Mining Law of 2015 encourages private companies to initiate mining activities beyond Earth, and the US National Aeronautics and Space Administration has contracted four companies to extract small amounts of lunar regolith by 2024, effectively launching the era of commercial space mining.[280] However, space mining remains controversial, with unanswered questions around who owns space and who will define the legal framework. Critics argue that the environmental impact is yet to be understood and that space mining could lead to conflicts among countries and companies.[281]

SPECIAL FOCUS 3.
THE PRECAUTIONARY PRINCIPLE

The precautionary principle is a principle for decision making whereby uncertainty around potential threats of major or permanent damage is used as a basis for action (or non-action). The Stockholm Declaration in 1972 laid out the grounds for the precautionary principle. Two decades later, the Rio Declaration contained the first formal definition of the precautionary principle, which is also the most commonly adopted definition. Since then, the concept has continued to be developed.

The precautionary principle can be understood as a decision-making approach based on balanced consideration of alternative options, benefits and risks. The precautionary principle is essential to avoid the (in many cases irreversible) harm to the environment posed by climate change. It guides decision makers to take, defer or avoid action in the context of scientific uncertainty in order to avoid future harm, while preventing unnecessary regulation and interventions. Despite the understanding of uncertainty, there is a requirement of “reasonable grounds for concern”.

The precautionary principle has shifted the burden of proof of the potential impacts of a project or policy away from those highlighting possible damaging consequences to those proposing activity to prove that the activity is not harmful. Continued investment in fossil fuel-based energy defies the precautionary principle, and such a view underpins the needs for increased renewable energy deployment and investment because this has much smaller scales of risk. Still, the low-carbon energy transition also involves risk, for example in relation to distributional and procedural justice, the availability of materials and financial capital. This calls for governing to ensure that the risks of the transition are mitigated.

The precautionary principle has been a significant factor in driving climate action and the adoption of renewable energy technologies. At the same time, it has faced criticism for being too ill-defined and because of its potential to be used as a tool to halt innovation. Essentially, the debate has focused on whether the uncertainty demands action, or whether a lack of evidence can be used as a reason for inaction and halting innovation; however, others have argued that the principle has actually been effective in steering innovation towards less-risky development pathways.

The precautionary principle relies on scientific knowledge of risk. Scientific knowledge involves uncertainty, as there is no absolute truth on complex issues. Therefore, how the precautionary principle is adopted involves political judgment and value prioritisation, so it is inevitably subjective and has potential for misjudgment. Robust use of the precautionary principle needs to acknowledge this.

Source: *See endnote 276 for this chapter.*

SOLUTIONS AND GOOD PRACTICES

The mining sector plays a key role in the renewable energy transition, as many of the materials needed for renewable technologies are sourced from mines. However, the sector faces many social and environmental challenges. To address these, possible solutions include policies and regulations, multilateral collaborations, and third-party verification of mining practices.

Policies and Regulations

Policies related to sustainable mining practices can focus either on the sustainability of mineral extraction within a specific country, or on the entire supply chain of a renewable energy technology (at the national or international level).

Within a country, inclusive solutions that address the rights of Indigenous Peoples in the extraction of critical minerals are essential (► see Energy Justice chapter).[282] Policies can ensure that Indigenous Peoples are included in the entirety of the decision-making process related to planning, permitting, regulation, monitoring, and evaluating, and that countries share the economic gains with them. In a step towards doing this, Canada has implemented a Critical Minerals Indigenous Engagement Strategy that prioritises the participation of Indigenous Peoples in the development of critical minerals projects.[283] This involves Indigenous Peoples in early-stage project planning and ensures that their concerns and perspectives are taken into account.

The US Department of Agriculture has updated its Policy and Procedure on Tribal Consultation to ensure that the agency engages in early, meaningful consultation with tribal nations on actions that may affect their rights, resources or trust responsibilities in relation to mining activities.[284] This includes providing opportunities for tribes to provide input on proposed actions and ensuring that their concerns are considered in decision-making processes.[285] Likewise, Sierra Leone's Mines and Mineral Development Act of 2022 requires mining companies to obtain the consent of local communities and grants women equal land rights, making it one of the world's most protective mining laws.[286]

An example of policies supporting sustainable supply chain practices is the introduction of climate and environmental and human rights protection into due diligence requirements, as is occurring with the proposed European directive on corporate sustainability due diligence. The directive is aimed at preventing human rights abuses and environmental damage in global supply chains.[287] It would require companies to conduct due diligence throughout their supply chains, identify and mitigate risks, and establish effective grievance mechanisms. The act would apply to companies operating in the EU, regardless of where their products are manufactured or sourced from, and would carry penalties for non-compliance.[288]

Multilateral Collaboration

Multilateral initiatives provide governments with the tools and resources they need to support sustainable mining practices, including data collection, technical capacity building and the sharing of best practices.

Data collection and analysis related to ASM mining is critical to understand and address the working conditions in the sector. The multilateral DELVE initiative serves as a global platform and knowledge exchange for the sector that includes resources and data.[289] Another data-focused multi-stakeholder partnership, the Extractives Industries Transparency Initiative (EITI), aims to strengthen accountability and governance of minerals and provides data to identify and close channels for corruption.[290] The EITI standard includes a set of principles and implementation requirements that extractive industries must comply with to ensure transparency and accountability. As of 2022, 50 countries had joined EITI and set up national multi-stakeholder groups to monitor compliance to the standard.[291]

Other multilateral initiatives that support sustainable mining practices include the International Council on Mining & Metals, the Intergovernmental Forum on Mining, Minerals, Metals, and

Box 9. The World Bank's Climate-Smart Mining Initiative

The World Bank's Climate-Smart Mining Initiative provides technical assistance and knowledge sharing to help resource-rich medium- and low-income countries navigate the transition to a low-carbon economy while also ensuring that mining is managed in a way that minimises its environmental and climate footprint. The initiative is based on four main principles: climate mitigation, climate adaptation, reducing material impacts and creating marketing opportunities:

- For climate mitigation, the initiative focuses on integrating renewables into the mining sector and implementing innovative extractive practices and energy efficiency in the mineral value chain. For example, the Chilian state-owned company Codelco installed the Pampa Elvira Solar Plant, which generates 54,000 megawatt-hours annually on average and supplies 85% of the power required by the division's SX-EW copper plant. According to official reports, the plant has led to a reduction in the mine's CO_2 emissions of 15,000 tonnes per year.
- Climate adaptation measures include "forest smart mining" with landscape management and resource efficiency in the mineral value chain, as well as innovation in waste solutions. For example, the World Bank is working with a mine in Ghana to implement a water management plan that will help the mine adapt to changing weather patterns and reduce its water footprint.
- The reducing material impacts principle focuses on the adaptation of a circular economy for critical minerals through the re-use and recycling of minerals and mineral supply chain management.
- The initiative also aims to create marketing opportunities for minerals supplied through low-carbon production cycles by de-risking investments and leveraging financial instruments, as well as robust geological data management.

Source: *See endnote 295 for this chapter.*

Sustainable Development (IGF), the Initiative for Responsible Mining Assurance (IRMA), Towards Sustainable Mining, the Responsible Minerals Initiative, the Responsible Minerals Foundation, and Women's Rights and Mining. These groups aim to set and publicise standards for human rights in all investments related to the mining of energy transition minerals, aligned with the UN Guiding Principles for Business and Human Rights as well as the Due Diligence Guidance for Responsible Business Conduct developed by the Organisation for Economic Co-operation and Development (OECD).[292]

As the largest inter-governmental initiative, IGF has 75 member countries and was founded during the UN World Summit on Sustainable Development in 2005, with a focus on mineral resource governance and sustainable mining practices.[293] It provides technical capacity building and shares best practices through its Mining Policy Framework to ensure that the minerals needed for renewable energy technologies are extracted in a sustainable manner.[294] Similarly, the World Bank's Climate-Smart Mining Initiative seeks to minimise mining's environmental and climate footprint (► see Box 9).[295]

However, some projects financed by international financial institutions have been criticised for their environmental impacts, their lack of transparency in decision making, and their failure to properly consult and compensate local communities and Indigenous Peoples (leading to land loss, displacement and negative impacts on livelihoods).[296] This highlights the importance for these institutions to enhance due diligence and effective engagement with local communities to ensure that mining projects are more sustainable. An example is the Amulsar Gold Mine project in Armenia: following complaints by non-governmental organisations, the International Finance Corporation (IFC) pulled its funding, as an Ombudsman report proved that the project did not comply with IFC standards.[297]

Third-Party Verification of Mining Practices

Independent verification of mining practices is essential to ensure that minerals are responsibly sourced and that environmental impacts are minimised. Illegal extraction of minerals contributes to human rights abuses, environmental degradation and other negative impacts on mining communities. Standards and certifications provide traceability, making it harder for illegally extracted minerals to be laundered into legal mineral supply chains.[298] With certification, downstream customers can gain greater assurance around sustainability in mining and metals supply chains, which is particularly important for critical minerals such as lithium, cobalt and rare earth elements used in the renewable energy transition.[299]

The Initiative for Responsible Mining Assurance (IRMA) is leading the way on third-party verification, with prominent lithium and nickel miners choosing to independently audit their operations against the IRMA Standard for Responsible Mining (► see Box 10).[300] The IRMA standard aims to incentivise more responsible extraction through transparency, inclusivity and rigorous independent verification.

Box 10. The Initiative for Responsible Mining Assurance (IRMA)

The Initiative for Responsible Mining Assurance (IRMA) is a non-profit organisation founded in 2006 by representatives of affected stakeholders, including non-governmental organisations, businesses, affected communities, mining companies and labour unions. Its mission is to ensure that mining operations respect the human rights and aspirations of affected communities, provide safe and healthy workplaces, minimise environmental harm and leave positive legacies. IRMA offers independent third-party verification for more socially and environmentally responsible mining of all minerals except fuel minerals. Its methodology and audit results are publicly available and provide information to everyone.

As a multi-stakeholder-led organisation, IRMA is accountable to all affected stakeholders. The governing board of directors includes two representatives from each of six stakeholder groups: mining companies, companies that purchase mined materials to make other products, non-governmental organisations, affected communities, organised labour, and investment and finance. Each stakeholder group has equal voice in IRMA's governance, making it the only global mining standard where civil society, communities and organised labour have the same voice as the private sector. If consensus cannot be achieved in decision making, then voting is used. If any stakeholder group is unanimously opposed (i.e., both representatives vote no), then a decision cannot be approved and discussions must continue until a resolution is found.

IRMA provides public, comprehensive reports of independent assessments of mine performance against strong environmental, social, and labour requirements, with the objective to provide stakeholders with the information needed to make informed decisions – whether they are purchasers sourcing materials, communities informing mining regulators, or mining companies improving their performance. Large electric vehicle manufacturing companies such as BMW, Ford and Tesla are among IRMA members, and multiple IRMA members have required their suppliers to source materials from IRMA-assessed mines.

Source: *See endnote 300 for this chapter.*

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REDUCING MATERIALS USE IN RENEWABLE ENERGY SUPPLY AND MITIGATING THE IMPACTS OF EXTRACTION

Renewable energy technologies require raw materials, including critical minerals. These materials are primarily sourced through conventional mining techniques, which are associated with considerable negative environmental and social impacts. Despite the challenges related to these materials, examples exist of potential measures to reduce these impacts and resource demands. These include both technological alternatives to some critical minerals and implementing the principles of circular economy (redesign, reduce, renovate, repair, re-use, recover and recycle). Regulatory frameworks and multilateral collaboration can also help to overcome these challenges. Table 6 provides an initial non-exhaustive overview of key solutions and good practices.

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TABLE 6. Solutions and Good Practices to Reduce Materials Use for Renewable Energy Supply Technologies and Energy Storage and to Mitigate the Impacts of Extraction

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Circularity in design and manufacturing (redesign and reduce)	Increased efficiency	Wind energy: Taller towers, larger rotors and lighter drivetrains to increase capacity factors and reduce material use per kWh ▪ Solar PV: Increased efficiency to reduce silicon and silver use per kWh ▪ E-mobility: More efficient induction motor technologies for electric vehicles
	Using alternative or fewer materials	Wind energy: Smaller magnets and/or replacement of permanent magnets ▪ Replacing balsa wood with polymers such as PET for blades ▪ Hydropower: Replacing stainless steel with composite materials in turbines ▪ Energy storage: Alternatives to lithium-ion batteries: iron-air batteries, lithium sulphur batteries, sand batteries, sodium-ion batteries, solid state batteries, thermal energy storage, pumped storage ▪ Overall: Use of biosourced materials
	Research and development	Design for recovering and recycling of turbine blades ***Examples:*** *Vestas in collaboration with Aarhus University, the Danish Technological Institute and Olin* *Siemens Gamesa's RecyclableBlade technology* *EU research projects such as MAREWIND, MODVION, REFIBER* *DecomBlades in Denmark*
		Design for disassembly, recovery and recycling in the PV sector ***Examples:*** *Research programmes of US National Renewable Energy Laboratory (NREL)* *IEA Technology Collaboration Programme on solar PV circularity* *EU Joint Research Centre*
	System changes to reduce energy use	***Examples*** *(Transport sector):* *Redesigning transport policies and infrastructure to enable shared e-mobility, public transport and active mobility*

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Circularity in the use of renewables (renovate, repair, re-use)	Extending the lifetime of renewable energy technologies	Retrofitting hydropower plants ▪ Refurbishing wind turbine components ▪ Extending the lifetimes of solar PV panels ***Examples:*** *Siemens Gamesa's wind turbine life extension programme* *Vestas re-winding generators* *Pilatus EU research project*
	Repurposing and re-using components	Reselling wind and solar system parts ▪ Repurposing retired electric vehicle batteries as storage units
	Certification standards	Certifying the quality of second-hand PV panels ***Examples:*** *CIRCUSOL* *Cradle-to-Cradle global certification programme*
	Capacity building programmes and skills certification	***Examples:*** *US Department of Energy programmes* *EU Directive (2009/28/EC) on technician accreditation*
Circularity at the end of life (recover and recycle)	Leveraging highly recyclable materials in renewable energy and energy storage technologies and in electricity networks	Recovery and recycling of PV panels ***Examples:*** *First Solar* *SolarCycle* *National PV Recycling Program of the US Solar Energy Industries Association*
		Recovery and recycling of turbine blades
		Recovery and recycling of battery materials ***Examples:*** *Redwood Materials* *Nth Cycle*
Removing barriers to unlock the potential of circular economy	Enabling policies and incentives for re-use, repair and recycling	Mandatory recovery and recycling ▪ Public procurement criteria ▪ Public subsidies ▪ Tax incentives ▪ Bans on landfilling ▪ Longer revenue stabilisation mechanisms ▪ Grants ***Examples:*** *EU Waste Electrical and Electronic Equipment (WEEE) Directive* *Legislation in the US State of Washington* *Australia and South Africa landfill bans* *Producer Responsibility Organisation (PRO) SOREN in France* *Decommissioning Fund in Japan*
Sustainable mining practices	Policies and market instruments for monitoring and enforcing sustainable mineral extraction	***Examples:*** *Canada's Critical Minerals Indigenous Engagement Strategy* *US Department of Agriculture's Tribal Consultation* *Sierra Leone's Mines and Mineral Development Act* *EU Corporate Sustainability Due Diligence Directive*
	Multilateral collaborations and initiatives for data collection and standards for human rights within the mining sector	***Examples:*** *DELVE platform* *Extractives Industries Transparency Initiative* *International Council on Mining & Metals* *Intergovernmental Forum on Mining, Minerals, Metals, and Sustainable Development (IGF)* *Initiative for Responsible Mining Assurance* *Towards Sustainable Mining* *Responsible Minerals Initiative* *Responsible Minerals Foundation* *Women's Rights and Mining*
	Technical assistance and knowledge sharing	Support for governments to implement responsible mining practices for minerals needed for the energy transition ***Examples:*** *World Bank's Climate-Smart Mining Initiative*
	Independent or third-party verification of mining practices	***Examples:*** *Initiative for Responsible Mining Assurance (IRMA)*

04

ENERGY JUSTICE

04

ENERGY JUSTICE

INTRODUCTION

Assessing the sustainability of energy systems from a holistic perspective requires a focus not only on the environmental impacts, but also on the social and economic dimensions. Energy systems are embedded in the wider social and economic environment.[1] Social and economic conditions such as income, equality, democracy, land and labour rights, and related policies and regulations all have an impact on renewable energy developments.

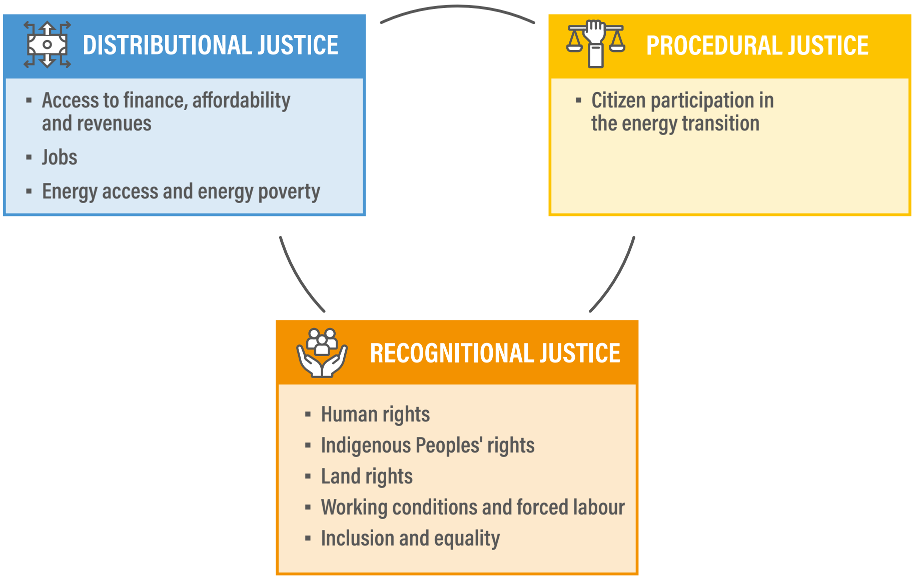
The fossil fuel-based energy system has had devastating consequences for both the environment and people.[2] Marginalised communities, such as low-income households, communities of colour, and Indigenous Peoples, as well as the lowest-income countries, are often the most negatively affected.[3] Globally, greater understanding of the unequal distribution of the burdens of environmental degradation and climate change has led to concepts such as environmental justice, climate justice and energy justice.[4]

Energy justice refers to a global energy system where the benefits and costs of energy services are distributed fairly, and where decision making around energy is both representative and impartial.[5] The concept of energy justice allows for broad examination of the social and economic challenges and opportunities related to energy and the ongoing transition from a fossil fuel-based to a renewable energy system. An energy justice lens supports the understanding of key considerations such as where injustices occur, how they should be resolved, which actors are included or excluded, and how best to recognise this.

To ensure that energy justice is core to the energy transition, it is useful to organise the concept around three cross-cutting themes. These are: 1) the distribution of resources needed to drive the energy transition in an equitable manner, 2) the recognition of energy justice, and 3) the procedural elements required for this transition (► see Figure 26).[6] Although they are not the only entry points, these three themes help frame the analysis of the most pressing issues of the energy transition.[7]

Distributional justice focuses on ensuring that the benefits and harms of energy-related activities are distributed as fairly as possible across society.[8] It refers to the physical allocation (or re-allocation) of energy-related benefits, the disadvantages, and how the responsibilities are distributed among different players.[9] It highlights that certain energy resources are attached to specific localities – affecting local communities – and that "energy poverty" is interlinked with access to resources.

FIGURE 26. Overview of Energy Justice Framework and Key Considerations of This Chapter



DISTRIBUTIONAL JUSTICE

- Access to finance, affordability and revenues
- Jobs
- Energy access and energy poverty

PROCEDURAL JUSTICE

- Citizen participation in the energy transition

RECOGNITIONAL JUSTICE

- Human rights
- Indigenous Peoples' rights
- Land rights
- Working conditions and forced labour
- Inclusion and equality

Source: *See endnote 6 for this chapter.*

Recognitional justice seeks to ensure that the divergent perspectives of different stakeholders are appropriately accounted for, regardless of gender, cultural, ethnic or social differences. It aims for a fair representation of opinions without (physical) threats, domination and devaluation, and misrecognition of perspectives.[10]

Procedural justice focuses on ensuring access to decision-making processes in multi-level legal systems, which can impact the just distribution of energy resources.[11] It is also linked to norms, values and resulting behaviours, beyond the "hard" regulatory rules.

The three tenets of energy justice make it possible to assess the social benefits as well as the potential negative impacts of the shift to a renewables-based energy system.[12] They can be seen as leverage points to propel a just transition (► see Box 11).[13]

Box 11. What Is a "Just Transition"?

The concept of a just transition first emerged in the 1970s in reaction to US efforts to regulate polluting industries under the National Environmental Policy Act. As part of these new rules, a fund was established to provide a minimum income and educational benefits to workers that had been exposed to chemicals and hazards, as a way to help them transition their livelihoods away from hazardous work. The concept later evolved to centre on trade unionists seeking to safeguard workers from the impacts of environmental protections on job security and other labour dynamics. For example, the International Trade Union Confederation has become active in shaping implementation and response measures in the climate field.

Today, the term "just transition" focuses broadly on efforts to seek more environmentally and socially sustainable labour outcomes. In the context of the Paris Agreement's goal to rapidly reduce greenhouse gas emissions by mid-century, the pace and scale of the needed energy transition is unprecedented in human history. Although the shift to renewables brings large environmental benefits, it also carries immense risks for vulnerable communities that depend on resource-extractive industries (► see Jobs and Employment in Renewable Energy section).

The OECD has developed the following recommendations on how to ensure a just transition:

- For communities dependent on fossil fuel extraction, investment in renewable energy with new industries and jobs is essential.
- Cities can invest in low- and zero-carbon transport, clean energy and circular economy principles.
- Industry can switch to renewable-based energy systems combined with clean industrial processes.
- Workers can opt for collective bargaining with clauses included on reskilling and redeployment in clean industries.
- Finally, governments and decision makers can embrace a just transition to tackle three challenges simultaneously: climate change, inequality and social inclusion.

Source: *See endnote 13 for this chapter.*

DISTRIBUTIONAL JUSTICE

A central question of the transition to renewable energy relates to who might benefit and who might be disadvantaged. This boils down to distributional justice. Inequalities may exist related to the affordability of renewables, access to finance, and the distribution of revenues, which in turn depend on wider socio-economic factors, regional developments, energy markets, and business and equity models. Also at issue is what the energy transition means for workers in the industries affected by this transition across different regions.

DISTRIBUTIONAL JUSTICE IN THE CURRENT ENERGY SYSTEM

It is widely acknowledged that burning fossil fuels is the leading contributor to climate change and pollution, and that these effects have disproportionate impacts on vulnerable and marginalised people and low-income countries.[14]

Oil and gas drilling and extraction result in air, soil, water and noise pollution; degrade and destroy natural habitats; and disrupt subsistence ways of life.[15] For coal, the environmental and social impacts of mining are well documented and include air and water pollution, soil erosion, biodiversity loss, and effects on human health and community cohesion in the vicinity of mines.[16] In the United States, studies note that coal-fired power plants are disproportionately located near low-income communities and communities of colour, resulting in significant health impacts for these populations.[17]

The large profits of fossil fuel companies are highly unequally distributed. In 2010, the CEO of a coal plant in the United States received an average annual compensation of USD 9.8 million, whereas a person living within 5 kilometres of a coal power plant earned an average income of USD 18,400.[18] Thanks to the recent record profits of the oil industry, the CEO of ExxonMobil Corporation received a reported pay package of USD 35.9 million in 2022, up 52% from 2021, when the ratio of CEO pay to median worker pay in the industry was 125:1.[19]

In the case of nuclear power, uranium extraction has been linked to substantial localised radioactivity.[20] The 2011 Fukushima nuclear accident in Japan resulted in the displacement of around 164,000 people from identified evacuation zones and nearby areas, and this population has since had to resettle in different locations across 47 Japanese prefectures.[21] In Niger, the closure of the Cominak uranium mine in 2021 due to depletion of the resource resulted in job losses for around 600 workers and contractors and left the region with around 20 million tonnes of


Alain Schroeder

residues that still contain 80% of their radioactivity – resulting in permanent ongoing exposure for nearby residents.[22]

DISTRIBUTIONAL JUSTICE AND RENEWABLES

Renewables bring opportunities for a more equitable energy system. In addition to being the least-cost power option in many instances, they offer the potential for multiple scales of deployment (from the utility scale to the household level), decentralised and democratised governance and ownership, and reduced environmental impact, especially when compared to fossil fuel energy sources and the traditional use of biomass.[23] Renewables are increasingly the fastest, most reliable and most affordable solution to provide energy access and alleviate energy poverty.[24]

Renewable energy technologies can be deployed almost anywhere to provide electricity, thermal energy for heating and cooling, and fuels for transport and other needs. They can be connected to an electricity grid or district heating network, or function as stand-alone systems, and can be combined with other activities such as agriculture, industry or leisure. They also allow for a variety of equity and business models.[25] When considering the renewable energy transition in the context of distributional justice, it is valuable to look at issues of affordability and access to finance, revenue generation and distribution, energy access/poverty, and employment.

Affordability and Access to Finance

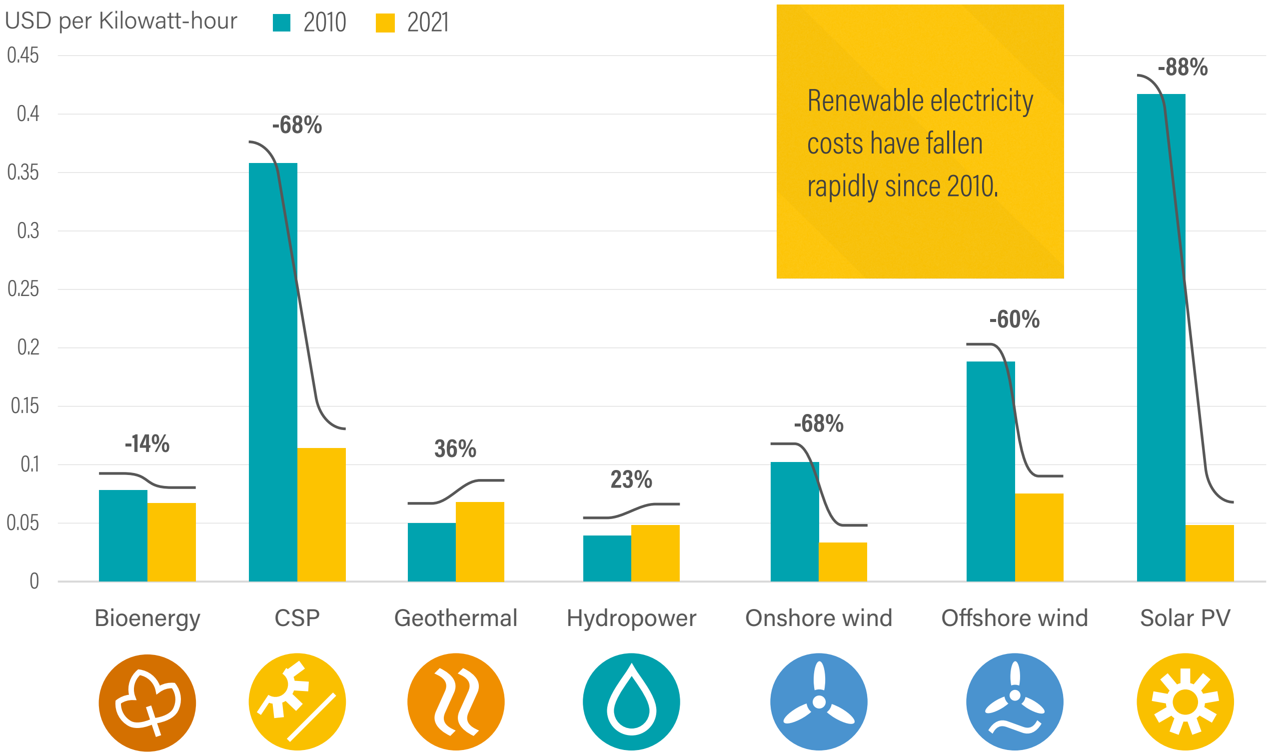
Status

Renewable electricity costs have fallen rapidly since 2010 (► see Figure 27).[26] In 2021, for the third year in a row, the per unit price of electricity generation from solar PV was below that of fossil fuels (although in some cases this rapid cost decline has since slowed).[27] For both solar PV and wind power, the levelised cost of electricity is below the range for fossil-based generation.[28] This means that in most cases, generating, buying and selling renewable electricity now offers a better value proposition than relying on utility companies to provide electricity sourced from fossil fuels.

Challenges

Despite the declining costs of renewable energy, substantial capital is needed to finance the upfront investment cost. However, the costs and available funding mechanisms for renewable energy projects vary widely and are unequally

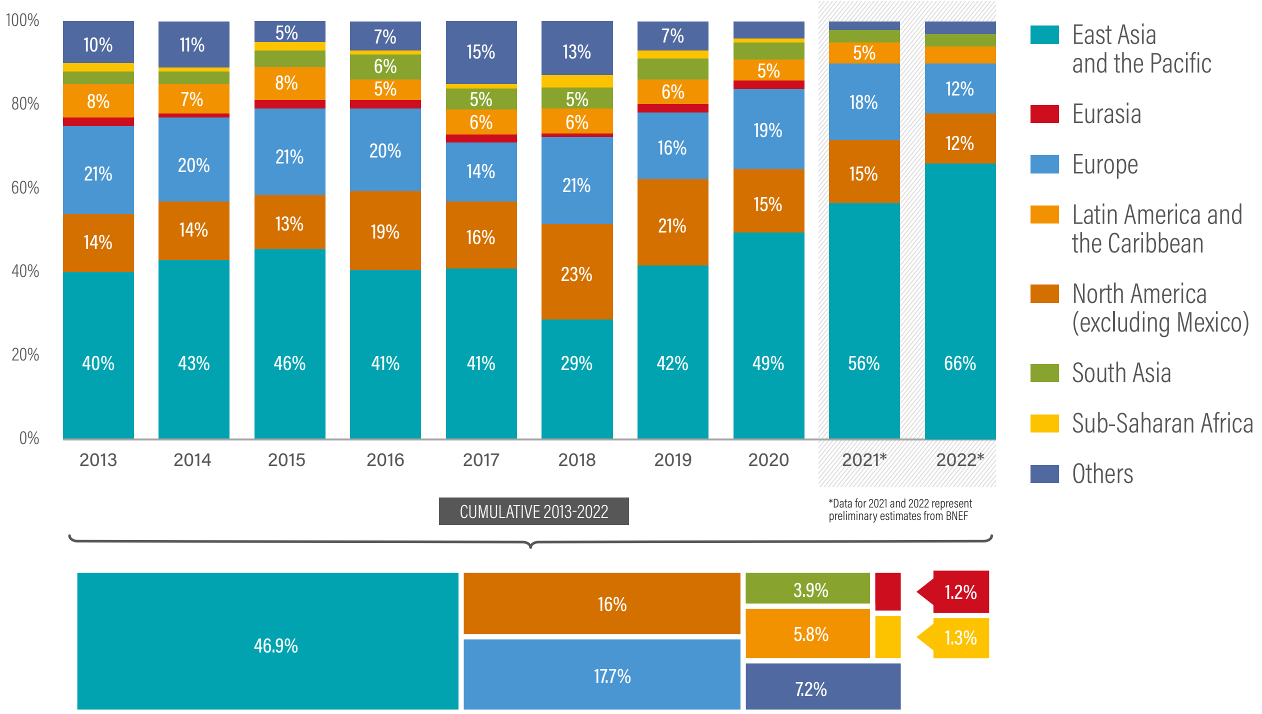
FIGURE 27. Levelised Cost of Renewable Electricity, by Source, 2010 and 2021



Renewable electricity costs have fallen rapidly since 2010.

Source: *IRENA. See endnote 26 for this chapter.*

FIGURE 28. Global Renewable Energy Investment by Region, 2013-2022



Source: *IRENA and CPI. See endnote 32 for this chapter.*

distributed.[29] When considering the sustainability of renewables, a key concern is whether the current financing and investment environment is actually enabling all countries and communities to install and deploy renewable energy technologies.

Globally, investment in renewables grew an estimated 2% annually during 2015-2020, then surged around 12% in 2020.[30] Total investment in renewables and energy efficiency reached USD 772 billion in 2022.[31] Regionally, this investment was highly unequally distributed, with two-thirds of it targeted at East Asia and the Pacific, of which more than 80% was in China (► see Figure 28).[32] The next highest investment was in Europe (USD 61 billion) followed by the United States (USD 59 billion).[33]

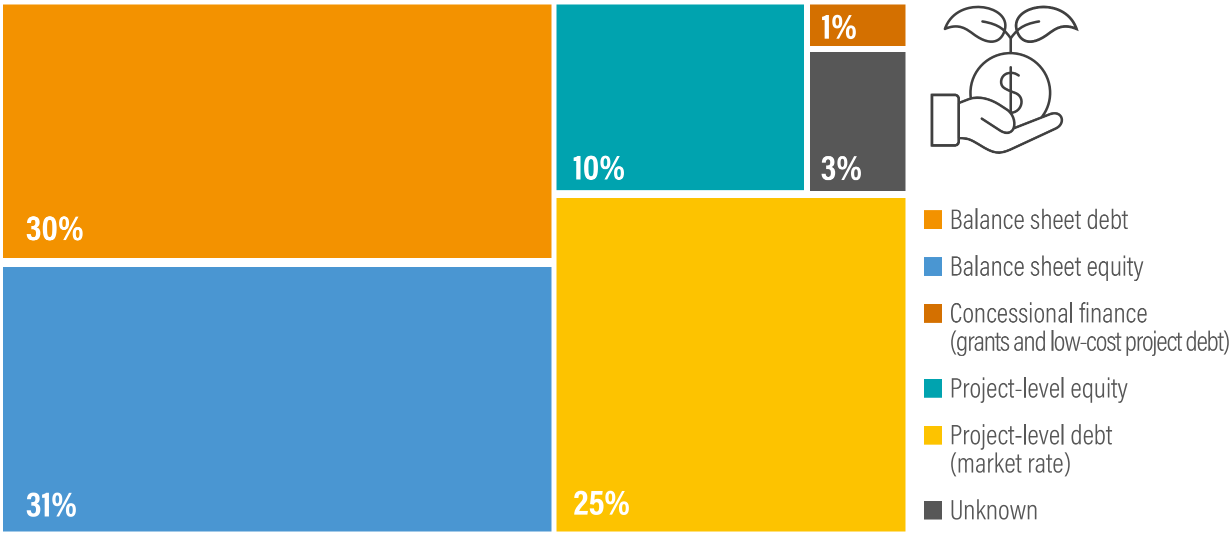
Global investment in renewables is expected to grow sharply in 2023 and beyond, due mainly to comprehensive policy packages in the United States and Europe.[34] In contrast, less than 10% (USD 75 billion) of the total renewable energy investment in 2022 went to 120 developing and emerging economies, with the biggest recipients being India and Brazil.[35] During the decade from 2013 to 2022, the African continent received only 2.4% of the global investment in renewables, of which only 1.29% went to Sub-Saharan Africa (► see Figure 28).[36]

For developed economies in East Asia, the EU, and North America (excluding Mexico), most of the investment in renewables (86%-89%) between 2013 and 2020 came from domestic sources.[37] Meanwhile, developing countries relied more heavily on international capital, with domestic investment accounting for only half of the total renewable energy investment in Sub-Saharan Africa and 61% in the Middle East and North Africa.[38]

The financial instruments that are available to project developers, as well as the conditions under which funds are allocated, shape the types of projects on the ground. The three main financial instruments are project-level financing and balance sheet financing (with equity or debt options for both), as well as grants.[39] Project-level financing entails transferring the risks of loans and insurance to a specific project, whereas balance sheet financing allows for transferring the risks to the global assets of a company. Thus, more mature businesses may benefit from better financing conditions than smaller structures when projects present higher financial risks.

In 2020, 61% of global renewable energy investment was allocated using balance sheet financing, with 31% as equity and 30% as debt.[40] Project-level equity accounted for only 10% of investment, while around 25% was allocated as project-level debt (at the market rate) (► see Figure 29).[41] Most of the investment (70%) was made by the private sector, whereas only 1% was allocated through grants (55% of these from governments) and through low-cost project debt (up to 93% from development finance institutions).[42] This 1%

FIGURE 29. Global Renewable Energy Investment by Financial Vehicle, 2020



Source *IRENA and CPI. See endnote 41 for this chapter.*

> Only 1% of investment was allocated through grants (55% of these from governments) and through low-cost project debt (up to 93% from development finance institutions).

of concessional finance was distributed unevenly among countries and regions, with Latin America and the Caribbean receiving more than one-third (37%).[43]

A key factor behind this inequity is that investments are mainly based on financial parameters such as perceived financial risks and potential investment returns, which do not reflect social and environmental benefits. Private capital, which accounts for the bulk of the investment in renewables, tends to flow into contexts that have favourable risk-return profiles, making access to finance more accessible for mature technologies and markets, and much more expensive for developing countries and small organisations.[44] To alleviate this challenge, governments and development finance institutions play a key role in setting a supportive policy framework (e.g., carbon pricing) and in providing public investment, de-risking investments to attract private capital, and adapting financial rules for low-income countries and communities (► see Solutions section).[45]

At the smaller scale, the upfront costs of renewables remain a barrier for middle- and low-income households even in developed countries.[46] Multiple investment vehicles are available to help individuals, small companies and community initiatives install renewable energy systems, such as rooftop solar PV, wind turbines and small-scale biogas digesters. Financing options include upfront loans for capital expenditures, power purchase agreements (PPAs), cash-out refinancing, and home equity lines of credit, as well as leasing of systems (► see Box 12).[47]

Solutions

Redirecting finance and investment to support more equitable access to renewables can take many forms. These include the reallocation of finance (or incentives) to support local and community-led co-operatives or citizen-owned renewable energy initiatives (► see Procedural Justice section) and allocating climate finance and other international funding specifically to low- and middle-income countries. It also includes encouraging sustainable finance and the use of environmental, social and governance (ESG) criteria; introducing taxonomies[i]; and more broadly integrating into regulatory frameworks the disclosure of high-quality, reliable, and comparable data, following harmonised climate disclosure standards to ensure system-wide alignment on sustainability in finance and investment.

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[i] In the context of sustainable finance, taxonomies are classifications that help in identifying what qualifies as sustainable economic activity.

Box 12. Public Financing Mechanisms for the Deployment of Renewables

Beyond the market developments facilitating the affordability and availability of renewables, governments can offer specific mechanisms to accelerate their deployment. Some examples are summarised below.

Net metering is a billing tool that credits producers of renewable electricity for any surplus they contribute to the grid, net of the amount they consume (generally over a specific billing period). For example, a household solar PV installation may generate more electricity than is used during daylight hours, which can be fed into the grid and credited against the electricity that residents draw from the grid at night.

Feed-in tariffs entail a mandated long-term price on electricity produced from renewable sources that is fed into the grid. Usually the price is more beneficial than the set market price for electricity. This allows for both a higher guaranteed price for producers as well as long-term price stability capable of securing returns on an investment.

Tax surcharges can be placed on energy consumed, with the aim of funding the deployment of renewables. In the Netherlands, such a levy is included on all bills, and it can be redeemed if one produces one's own power from clean sources, or if a back-up installation is in place that can help to alleviate disruptions in the grid.

General subsidies help reduce the upfront cost of any kind of investment. In the case of the energy transition, most subsidies go towards investments in energy efficiency improvements as well as in public and clean transport, followed by renewables.

Carbon pricing can support the uptake of renewable energy technologies by pricing out fossil fuels. Carbon pricing is a financial tool that helps capture the costs of greenhouse gas emissions, such as the impacts of droughts on crops, loss of property due to floods and sea-level rise, and the health-care costs of heat waves.

Source: *See endnote 47 for this chapter.*

Sustainable finance has gained momentum as a way to use ESG criteria in finance and investment and to fund projects that prioritise a triple-bottom-line (considering people, the environment and the economy).[48] Such an approach puts broader value creation at the centre of business, beyond simply generating a profit. ESG issues are becoming central to assessing a company's impacts on the environment and on stakeholders, as well as the risks that companies themselves may face in light of a changing world.[49] ESG information is particularly relevant for impact investors interested in shifting their capital towards sustainable solutions. However, ESG investing has been criticised for insufficiently capturing harms to people and the resulting risk to business.[50] Tools aimed at driving "just transitions" have emerged that help to better capture the socio-economic realities and challenges of transitions.[51]

There is a push to standardise and increase the transparency of information on investments, including those in the renewable energy sector. For example, under landmark legislation related to the EU's Corporate Sustainability Reporting Directive, large companies, as well as listed small and medium-sized companies, will be required to disclose much more detailed non-financial and/or sustainability information than previously.[52] In addition, the International Sustainability Standards Board recently issued its first sustainability disclosure standards, IFRS 1 and IFRS 2, aimed at increasing the confidence in company sustainability disclosures as a basis for investment decisions.[53]

Interest also is rising in **sustainable finance taxonomies**, which help to classify what qualifies as sustainable economic activity.[54] Taxonomies allow for greater market transparency, which can reduce uncertainty and enable institutional investors to target their investments with an impact lens.[55] Ideally, such efforts will incentivise decarbonisation in the private sector and help the public better understand how business actors are approaching their energy use and climate-related risks.

A key form of sustainable finance – **climate finance** to support mitigation and adaptation activities in developing countries – has become an important topic in international climate discussions. Under the Cancun Agreement in 2010 (following the United Nations Climate Conference in Copenhagen, COP 15), high-income countries committed to providing low-income countries with financial resources (USD 100 billion per year by 2020) to implement the objectives of the UN Framework Convention on Climate Change (UNFCCC).[56]

In 2020, climate finance, including public investment from governments and development financial institutions, and the private sector, totalled USD 632 billion.[57] Of this amount, public climate finance from developed to developing countries made up USD 68.3 billion.[58] Climate finance was a key topic at the 2022 UN Climate Conference in Sharm El-Sheikh, Egypt (COP 27), with the final agreement revising the initial 100 USD billion per year and highlighting the urgency of investing USD 4-6 trillion annually in renewable energy, technology and infrastructure until 2030 if net zero greenhouse gas emissions are to be achieved by 2050.[59]

Mitigation received the largest share of climate finance in 2020, and energy was the largest target sector, receiving USD 334 billion (more than 90% of it for solar PV).[60] Low-carbon transport is the fastest growing industry sector for climate finance, with funding growing 23% in 2018.[61] A related initiative is **climate bonds**, which aim to drive down the cost of capital for climate projects, contribute to the aggregation of fragmented sectors and support governments in working with debt capital markets.[62]

Additional initiatives have sought to mobilise finance for the energy transition in low-income countries. The Glasgow Financial Alliance for Net Zero (GFANZ), launched in 2021, brings together existing and new finance initiatives targeted at achieving net zero greenhouse gas emissions. As of 2022, 450 financial firms in 45 countries, representing combined assets of more than USD 130 trillion, had committed to mobilising private capital for emerging markets and developing economies through private sector investments and public-private collaboration.[63] In 2022, the International Monetary Fund launched its Resilience and Sustainability Trust, which helps low-income and vulnerable middle-income countries build resilience by contributing to a stable balance of payments.[64]


Abbie Trayler-Smith / Panos Pictures / Department for International Development

Just Energy Transition Partnerships (JETPs), launched in 2021, aim to finance the decarbonisation of fossil fuel-intensive economies. The first JETP was convened when France, Germany, the United Kingdom, the United States and the EU committed to mobilise USD 8.5 billion for the energy transition in South Africa.[65] Since then, similar partnerships have extended to India, Indonesia, Viet Nam and Senegal and have involved more donors, including multilateral development banks, national development banks and development finance agencies. Because JETPs involve a relatively small group of actors, they could potentially accelerate energy transition investments in developing countries.[66] The approach has been lauded as impactful, despite criticism that the first JETP was a loan and not a grant, ultimately adding pressure on South Africa's economy.[67]

Policy de-risking instruments aim to support renewable energy policy design, the building of institutional capacity, and overall assessments of grid capacity, resource availability and the development of skills for local operations and maintenance.[68]

✓ Through just transition action plans governments can outline pathways and identify the investments needed for moving away from fossil fuel-intensive economies.

This can be paralleled with financial de-risking instruments, which transfer risks to public actors such as development banks. Such instruments include loan guarantees, political risk insurance and public equity co-investment.[69]

Through just transition action plans and transition taxonomies, governments can outline their proposed pathways for moving away from heavily coal-based and fossil fuel-intensive energy systems, as well as their investment needs for making these transitions possible.[70] The aim is to prepare governments for the best possible options when the social and economic circumstances emerge. This means that decision makers need to take stock early-on of where transitions are taking place – especially in carbon-intensive industries – and to plan for various risks (geographical, financial, time and skills related).[71] Notable examples of just transition action plans include those from the US state of Colorado and the Just Transition Planning Framework in Scotland.[72]

Special funding vehicles can be considered to enhance a fair distribution of costs and benefits. For example, credit and savings co-operatives can be used to pool the financing of renewable energy projects, especially in low-income countries where members may have the savings but not the collateral to apply for bank-based loans.[73] By creating a member-owned financial institution, entities can aggregate their finances and make decisions about investments together. In Europe, the REScoop MECISE is a mutual fund established to finance energy co-operatives across the region.[74]

Box 13. Emerging Equity and Business Models for Renewables

Many different business models exist for the ownership and deployment of renewable energy projects. These define not only the size and form of projects, but also how they are deployed and who benefits from the value created. The energy system has traditionally been centralised, focusing on large-scale actors, but the modular potential of renewable energy technologies, alongside technological and policy innovation, have encouraged decentralisation, increasing the diversity of business models and opportunities for small-scale actors.

Decentralised wind and solar energy projects, deployed close to consumers through micro-generation and community energy projects, have been a key driver of public participation in the generation of renewable electricity (and, increasingly, of renewable heat).

Some emerging renewable energy business models and case examples are presented below.

Pay-as-you-go: In this model, a solar PV system is sold or rented in exchange for a regular payment and can be remotely disconnected in the case of non-payment. The benefits of the model include improving off-grid energy access and enabling other business models such as community ownership and peer-to-peer trading.

Energy as a service: This refers to the provision of energy-related services, such as project implementation and energy efficiency improvements, in addition to providing the energy itself. The key benefit of the model for consumers is improved energy performance – for example, decarbonisation or reduced energy costs. Examples include offering long-term PPAs for solar PV electricity or solar heat purchase agreements where the solar energy producer owns the installation and bears the risks, but is ensured a fixed rate for the energy produced, which reduces investment risk.

Co-ownership and co-operative models: Such models are based on the principles of the International Co-operative Alliance. They are aimed at stronger democratic member control, one-vote-per-actor decision making and stronger membership economic control (► see Community Engagement section).

Aggregation: In this emerging model, distributed energy resources are pooled, resulting in a similar capacity to that of conventional energy generators. Aggregation entails a group of agents acting as a single entity in the energy market. Aggregators can increase flexibility in the energy system as well as decrease energy prices. Examples include a project involving the South Australian government and Tesla to build a virtual power plant, and California's Community Choice Aggregators (CCAs) for clean energy.

Peer-to-peer trading: This refers to the free trading of electricity between producers and consumers through the electric grid and without an intermediary. Such trading empowers consumers and prosumers (individuals who both consume and produce energy), increases renewable energy deployment on the grid, and can also lead to balancing congestion management and providing ancillary services. In the United Kingdom, the Power for People group has drafted a Local Electricity Bill (under debate in parliament as of September 2023) that would grant community energy projects the legal right to sell electricity directly to consumers, thereby boosting community energy by improving project viability.

Source: *See endnote 76 for this chapter.*

Marcela Gara / Resource Media

Enhancing the financial resilience of investments in renewable energy projects can also be done by building hybrid models such as energy generation combined with agriculture activities. This means that for small-scale investments, diversifying the potential revenue sources can raise the resilience of the investment and the plant.[75]

Revenue Generation and Distribution

When assessing the affordability of renewables, it is useful to look at how revenues are generated, and at different scales, to understand how this revenue can ensure the viability of the project over time, while supporting a just transition among the diverse players.

Status

The potential for revenue generation from renewable energy projects varies widely depending on the business model and equity structure, as well as on the financial and regulatory environment (► see Box 13 for an overview of emerging equity and business models).[76]

Service-based business models emphasise delivering value directly to end-users through private or public utilities, co-operatives, non-governmental organisations or private companies. These models centre around consumer fees based on consumption or energy savings.[77]

Medium- and large-scale or grid-connected projects rely on public-private partnership in the form of build-own-operate-transfer (BOOT) or multi-party or private ownership. Revenue streams can stem from selling electricity to national grids (or to utilities) or directly to customers – for example, at a fixed price regulated as a


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feed-in tariff or as set out in a PPA – or at a market price. A lease or hire purchase model underlines the versatility of renewable energy business strategies, as it allows end-users to acquire equipment through instalment payments, with a leasing company providing the equipment for a contracted period, and ownership potentially transferring to the user at the end of the contract.[78]

Benefits

Renewables allow for a variety of business models and equity structures, enabling new and small actors to participate actively in the energy system.[79] Renewables can be community-owned, generating local revenues and employment.[80] Some studies have shown that community-owned renewable energy projects empower residents and co-operatives to invest in and own a stake in installations, generating a return on investment that enhances the local economy.[81] This approach aligns with principles of procedural justice, creating a fairer and more inclusive energy transition (► see Procedural Justice section).[82]

Challenges

Renewable energy projects encounter specific challenges related to project development and revenue generation. These include market price volatility, regulatory and policy changes, inflation, changes to operational and maintenance costs, off-take agreement risks (particularly in the event of payment defaults), and vulnerability to natural disasters and extreme weather events. Navigating these complexities demands strategic planning and adaptability for sustainable success.[83]

One of the main ways in which governments have supported large-scale project deployment in recent years has been by holding renewable energy auctions, which can draw in substantial investors and achieve competitive pricing. However, meeting low price targets may prevent small and new players from competing in such tenders against well-established large companies. The significant administrative expenses involved, such as meeting qualification criteria, can create obstacles for these smaller and newer participants, potentially resulting in the dominance of larger players in the market.[84] Small and new players also encounter barriers to entry resulting from mechanisms such as project size allocation or technology-specific auctions that potentially benefit larger, well-established entities.[85]

Solutions

How business models and equity structures are designed can profoundly influence revenue outcomes for renewables.[86] Understanding the nuances of these models and tailoring them to specific contexts is instrumental in unlocking revenue potential. By aligning revenue generation strategies with the unique characteristics of specific projects, stakeholders can maximise economic benefits and help to foster a just energy transition.[87]

Auction designs can employ various strategies to reduce barriers and promote the engagement of small and emerging participants, including local communities.[88] This includes setting aside a predetermined allocation of opportunities for local, small, and new players, implementing technology-specific auctions with project size limitations to level the playing field, extending preferential treatment such as discounted bid bonds and relaxed qualification requirements, and adopting less stringent compliance rules. These measures can encourage wider participation, leading to the growth of local supply chains and industries and thereby fostering economic development.[89] (► See also the solutions in the Affordability and Access to Finance section.)

✓ Auction designs can promote the engagement of small and emerging participants, including local communities.


Abbie Trayler-Smith / DFID

Energy Access

Status

In the decade between 2010 and 2020, 45 countries achieved universal access to electricity for their populations.[90] Despite this progress, energy access remains a pressing concern globally, with 675 million individuals lacking access to electricity in 2021, including 80% of people in Sub-Saharan Africa.[91] As of 2022, 113 countries still did not have universal electricity access, with 25 of these countries aiming for universal access by 2030, 29 countries seeking to enhance access and 59 countries with no established targets.[92] Meanwhile, around 2.3 billion people lacked access to clean cooking solutions and were relying on traditional biomass or polluting fuels for cooking.[93]

Despite advancements in urban electrification, rural areas continue to face significant access challenges.[94] Such disparities underscore the urgency of implementing sustainable solutions. Renewables can help to provide more affordable and reliable electricity supply, more modern and efficient cooking appliances and cleaner cooking fuels for low-income households.[95]

Benefits

Decentralised renewable energy is the fastest, most effective and least-cost solution to improving energy access.[96] Between 2012 and 2021, the number of people who gained access to electricity through off-grid renewable-based systems more than doubled, from 19 million to 41 million.[97] Moreover, 48 million people globally were connected to around 21,500 mini-grids as of 2022, with a total capacity of 7,224 MW[i],[98]

✓ Distributed renewable energy is the fastest, most effective solution to improving energy access.

Transitioning to renewable energy can enhance energy security, promote economic growth, and enable marginalised communities to access modern energy services. Decentralised renewable energy solutions can be tailored to local contexts, respecting cultural and environmental considerations.[99] Distributed renewables can support productive activities such as agriculture, animal husbandry, textiles, crafts and micro-businesses.[100] During extreme weather events, portable renewable energy technologies have proven crucial in providing equipment to affected populations and emergency response teams.[101] Distributed renewable energy systems allow for essential rural health-care services such as vaccine preservation, and also support urban facilities in case of unreliable grids or supply shortages.[102]

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[i] Around half of the installed mini-grids are powered by solar energy, followed by hydropower (35%) and fossil fuels (10%). See endnote 98 for this chapter.

Renewable energy targets for rural electrification and regulatory frameworks create a pathway for the deployment of renewable technologies in underserved regions.

Renewables-based cook stoves, water pumps and cooling technologies can improve the quality of life for people living in remote areas, especially for women (► **see also the Gender Equality section**).[103] Renewable-based electrification, solar thermal and advanced bioenergy systems can play an important role in providing access to clean cooking.[104]

Challenges

Despite record investments and installations in renewable energy, significant challenges persist.[105] Although investment in renewables reached a historic high in 2022, due to the uneven distribution of investments, the number of people lacking electricity access globally was projected to increase by 20 million that year.[106] Achieving universal electricity access remains a complex task, especially in rural and remote regions. Balancing the costs of infrastructure development, technological solutions, and affordability for communities with limited financial resources poses a substantial challenge.[107]

Solutions

Governments, non-governmental organisations and international bodies play critical roles in improving energy access (► **see Affordability section**).[108] Renewable energy targets for rural electrification and regulatory frameworks can create a pathway for the deployment of renewable technologies in underserved regions.[109] Recent examples include India's Policy Framework for Decentralised Renewable Energy Livelihood Applications and Nigeria's Integrated Energy Plan.[110] Nigeria's plan targets installing 5 million solar home systems in sparsely electrified areas, and providing access to electric cooking for 3.5 million households and to biogas cooking for 4.3 million households.[111]

Quality control and monitoring enhance the efficiency and effectiveness of renewable energy solutions, leading to lower energy system cost and facilitating energy access.[112] To address the lack of clean cooking solutions, interventions can encompass policy frameworks, technical standards, and community engagement, to ensure clean cooking access for all.[113] The adoption of quality standards, such as the International Electrotechnical Commission (IEC) standards for solar kits, can ensure reliable and affordable decentralised renewable systems.[114] Emerging business models, such as "pay-as-you-go", can allow for low-income households to afford small payments while controlling their energy use.[115]

Tackling Energy Poverty

Status

The term "energy poverty" relates to the unequal access to affordable modern energy services, both geographically and among socio-economic classes.[116] This issue is prevalent in both developing and developed countries.[117] Beyond the energy access problem (► **see Energy Access section**), energy poverty refers to situations where modern energy is available but is financially unattainable for low-income households. In developed countries, energy poverty is defined as occurring when a significant share of a household's income is directed towards energy utility bills or when energy consumption must be curtailed, negatively affecting residents' health and well-being.[118]

Benefits

Renewable energy, in tandem with innovative financial mechanisms and community-driven initiatives, can serve as a powerful catalyst in the fight against energy poverty, reducing energy bills through self-consumption or even generating revenue, and empowering vulnerable households (► **see Solutions section for examples on how renewables can alleviate energy poverty**).[119]

Challenges

While the imperative to address energy poverty is high, specific challenges persist in improving energy performance for vulnerable groups.[120] Awareness of renewable energy and energy efficiency interventions is often limited among inhabitants, posing difficulties in engaging them in projects. Vulnerable households are not homogenous. Usually, the most vulnerable people are the most at risk of experiencing energy poverty: older people, single parents, low-income households and minorities. Moreover, it can be challenging to access these people, making it hard to identify instances of energy poverty. Individuals that are experiencing financial difficulties may be reticent to discuss their situation, hindering the identification of those in need. The absence of a standardised definition of energy poverty complicates accurate measurement and indicator selection.[121]

Comprehensive renovations to improve energy efficiency and the integration of renewable energy systems are often the best solution, although accessing funds for these higher-cost interventions can be problematic.[122] These challenges are particularly pronounced in older social and public housing, where deep renovations are needed. The owner-tenant dilemma further exacerbates the issue, as owners lack incentives to invest in energy efficiency when tenants are responsible for energy bills.[123]

Solutions

In regions where energy access is available, the complexity of energy poverty stems mainly from insufficient household incomes, high energy costs and poor energy efficiency.[124] To address this, targeted policies are needed, aligning with these three dimensions of energy poverty.[125] Efficiency measures – such as insulation, retrofitting and efficient appliances –


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✔ Renewable energy, in tandem with innovative financial mechanisms and community-driven initiatives, serves as a powerful catalyst in the fight against energy poverty.

can alleviate energy poverty by reducing the overall energy demand.[126] Combining these measures with renewables aligns with climate goals and avoids overinvestment in underutilised assets.[127] At the household level, renewable energy can result in savings on utility bills (dependent on regulations and on geographical proximity to mature energy systems).[128] Because different places face different energy poverty challenges, tailored solutions are needed across multiple levels and across differing geographies.[129]

In Portugal, structural measures such as building retrofits and renewables, as well as innovative financing for building owners and tenants, have helped to address year-round energy poverty, yielding benefits in healthcare, air quality, climate resilience, productivity and social cohesion.[130] In Bulgaria, the Energy Agency of Plovdiv, inspired by successful models in Spain and France, tackled energy poverty by installing solar PV plus storage in social housing, which enhanced self-consumption and self-sufficiency and protected vulnerable residents from rising energy costs.[131] Romania's Alba Iulia Municipality addressed high energy bills and achieved energy savings by using smart monitoring solutions and behaviour change measures in an energy-efficient social housing building.[132] In France, an innovative energy savings company (ESCO) model involving citizen energy communities and local services promotes renewable heating technologies in vulnerable households, with costs repaid from savings on energy bills.[133]

For both communities and individuals, investing in renewables can result in returns that can be captured and redirected to other uses, depending on the type of financing and business model used (► see Boxes 12 and 13).[134] Through mechanisms such as net metering, any surplus energy generated can be fed back into the grid or traded, resulting in credits or payments and allowing households and communities to offset energy costs or even generate revenue. These financial gains can be strategically allocated to other vital needs.[135]

Public authorities can implement a variety of local solutions: targeting residents that are most vulnerable, retrofitting social housing stock, providing trusted energy advice to residents, introducing campaigns targeting less-wasteful energy use, accelerating the deployment of fossil-free heating systems, introducing demand-side flexibility measures and promoting clean mobility solutions.[136]

Jobs and Employment in Renewable Energy

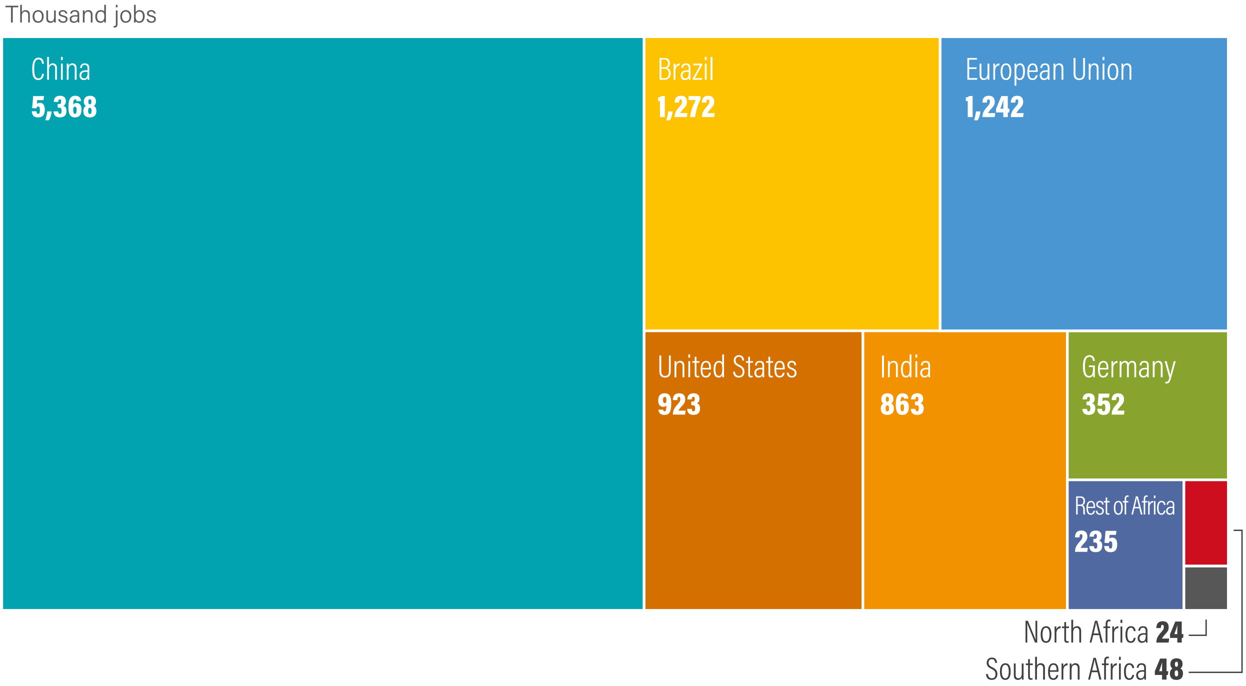
Status

In 2019, around 65 million people worked in energy and energy-related sectors [i], comprising 2% of the global formal workforce.[137] Renewable energy employment totalled an estimated 12.7 million in 2022 (0.4% of the global workforce).[138] The majority of renewable energy jobs are found in Asia, with China alone accounting for nearly half of the global total (around 5.4 million) (► see Figure 30).[139] Most renewables jobs (nearly 34%) are in solar PV, followed by liquid biofuels and hydropower (around 19% each) and wind energy (around 11%) (► see Figure 31).[140]

The types of renewable energy jobs differ regionally. In China, the majority of jobs are upstream positions related to solar PV manufacturing and hydropower, whereas in Brazil and the United States the liquid biofuel industry boasts the largest share of employment.[141] In the EU, the wind industry leads in renewable energy jobs, followed closely by solar PV.[142] Global supply chains also shape the job market, with around two-thirds of renewables jobs in China being in manufacturing, two-thirds in the United States being in construction and installation, and the vast majority in Brazil related to biofuels.[143] The types of skills that are required are evolving as well: for example, in South Africa an estimated 70% of new jobs are expected to belong to the high-skilled labour group.[144]


Kunal Gupta / Climate Visuals Countdown

FIGURE 30. Global Renewable Energy Employment by Country/Region, 2021



Source: *IRENA and ILO. See endnote 139 for this chapter.*

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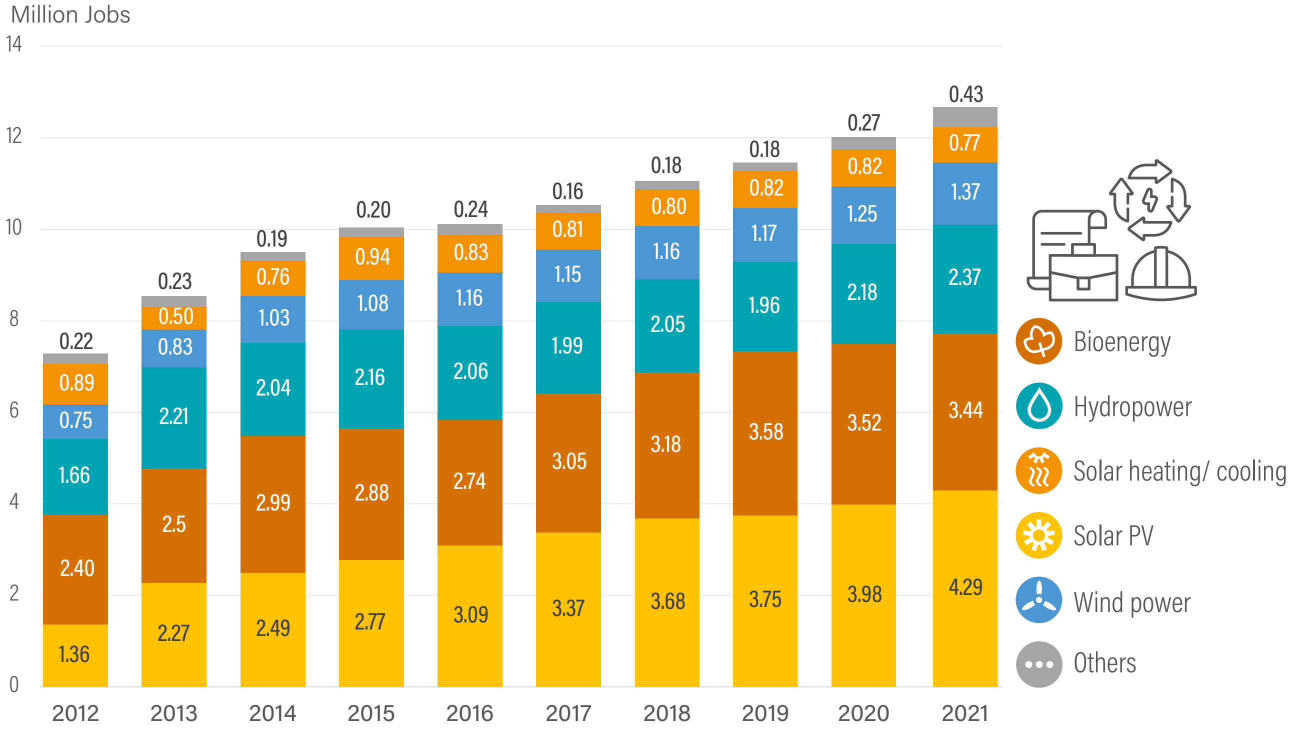
i As of 2019, 6.3 million jobs were in the supply of coal and 11.8 million in the supply of oil and gas. Power generation accounted for 11.3 million jobs, of which 3.4 million were in fossil fuel power plants. See endnote 137 for this chapter.

FIGURE 31. Global Renewable Energy Employment by Technology, 2012-2021



Source *IRENA and ILO. See endnote 140 for this chapter.*

Benefits

Meeting the goals of the Paris Agreement will require the creation of a significant amount of new jobs in renewable energy and associated sectors. One estimate suggests that as many as 18 million more renewable energy jobs can be created by 2030, bringing the global total to around 30.7 million; at least 5 million additional jobs would be needed to manufacture and install enough renewable energy capacity to meet a Paris Agreement-aligned scenario to keep global temperature rise within 2 degrees Celsius.[145] Other scenarios suggest that jobs in renewables could total 38.2 million by 2030 (► see Figure 32).[146] Emerging positions include technicians and installers, construction managers for large-scale solar and wind power installations, and project planners and engineers (working on both physical and software aspects of the transition). In addition, administrative, legal and business skills are needed to help steer the overall energy transition.[147]

The renewable energy industry was a key driver of employment in several developing countries in 2022, including Ethiopia, India, Kenya, Nigeria and Uganda.[148] In most of these countries, the majority of jobs in renewables are formal, in contrast with the high shares of informal employment in their overall labor market; there is a higher rate of high-skilled employment in more mature renewable energy markets.[149]

Challenges

The energy transition is driving important changes in labour dynamics. These include not only quantitative changes in the number of people employed in the renewables and fossil fuel industries, but also qualitative shifts in the kinds of jobs available, the skills required, the regions and industries affected, and possible temporal misalignments.[150]

Decarbonising the energy system requires phasing out fossil fuels. The coal sector alone is projected to lose around 2 million jobs, mostly in Asia, while the oil and gas industries may see a further 600,000 jobs lost by 2030.[151] This highlights the need to skill and re-skill workforces, particularly as many of the skills held by the fossil fuel workforce also can be used in the energy transition.[152] Reskilling programmes are widespread, including in the EU, South Africa and the United Kingdom (► see Solutions section).[153] Overall, the global growth in renewable energy jobs is set to exceed the number of jobs lost in the fossil fuel sector, as by 2030.[154]

Solutions

The energy transition offers key opportunities for job creation, training and skilling, provided that supports are in place to guide a just transition and create decent jobs[i].[155] With appropriate

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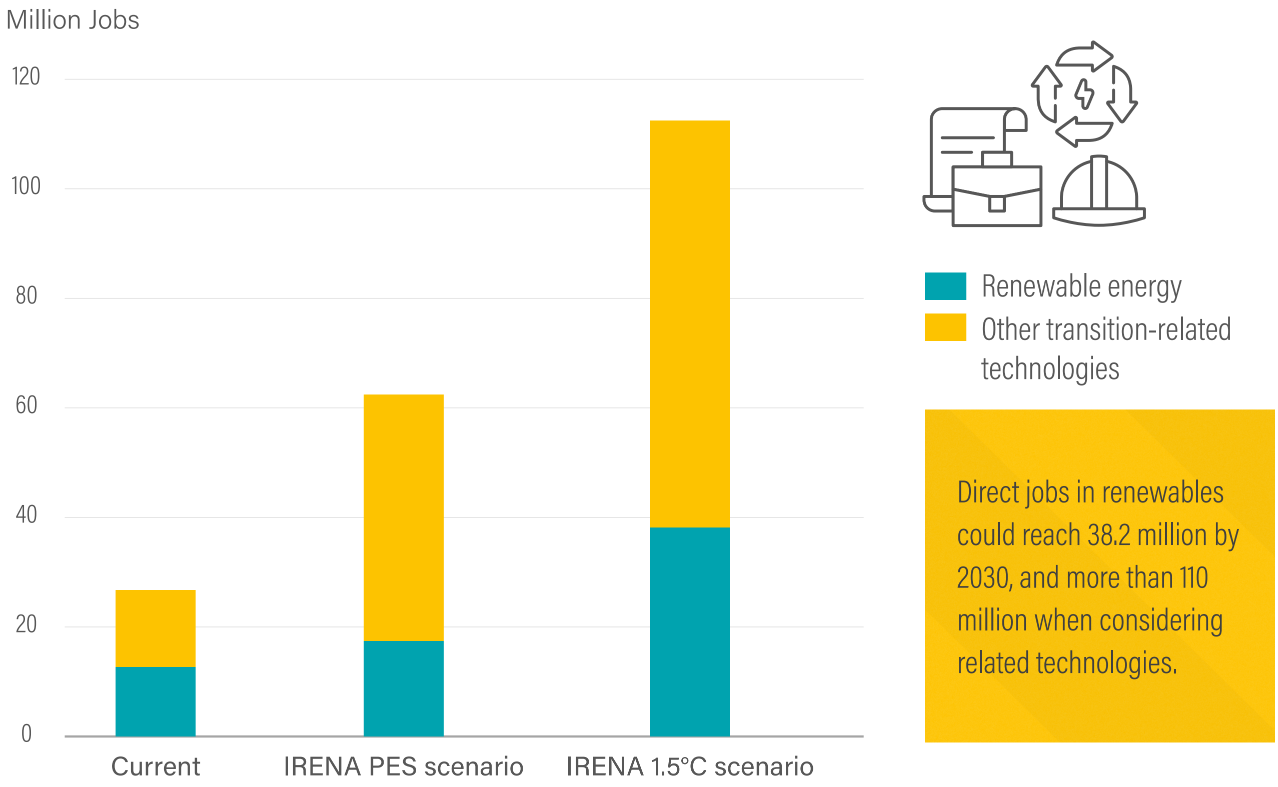
[i] According to the International Labour Organization's Decent Work Agenda, decent jobs seek to "promote decent and productive work for women and men in conditions of freedom, equity, security and human dignity", based on four strategic pillars: full and productive employment, rights at work, social protection and the promotion of social dialogue. See endnote 155 for this chapter.

FIGURE 32. Potential Employment in Renewables and Other Energy Transition-Related Technologies for 2030



Direct jobs in renewables could reach 38.2 million by 2030, and more than 110 million when considering related technologies.

Note: IRENA's 1.5°C Scenario describes a pathway for the energy transition that is aligned with the goal of limiting the increase in the global average temperature by the end of the 21st century to 1.5°C, relative to pre-industrial levels, while prioritising readily available technologies. IRENA's Planned Energy Scenario reflects only governments' existing energy plans, targets, and policies, with a focus on the G20 countries. "Other transition-related technologies" include energy efficiency, electric vehicles, power systems and flexibility.

Source: *IRENA. See endnote 146 for this chapter.*

policy approaches to (re)training the labour force, jobs in renewables can provide opportunities both for people newly entering the workforce and for those facing job losses in the fossil fuel industry.[156]

One solution is to introduce reskilling programmes that target the shrinking fossil fuel workforce. The International Energy Agency has identified five archetypes for reskilling programmes: 1) skills training for renewables, which includes South Africa's Renewable Energy Independent Power Producer Procurement Programme and the EU's skills agenda; 2) reskilling specifically for coal workers, such as through Spain's Just Transition Strategy and the Romanian Wind Energy Association training schools in coal regions; 3) retraining workers in the oil, gas and auto industries, for example through the UK's Green Jobs Taskforce and North Sea Transition Deal, the US hydrogen workforce development programmes, and electro-mobility training programmes created by companies such as Volkswagen; 4) academic and corporate programmes focused on reskilling; and 5) programmes targeting under-represented groups such as youth, women and marginalised communities, for example Canada's Student Energy Solutions Movement and Brazil's RevoluSolar project.[157]

In Spain, a Just Transition Strategy was established in 2019 to support the transformation of carbon-intensive economic sectors. Codified in Spanish law, the Strategy involves creating a governmental body – the Just Transition Institute – and establishing an Urgent Action Plan to provide support and training opportunities to workers impacted by the closure of coal-fired power plants.[158] At the national level, the government, private companies and workers' unions signed tripartite agreements to ensure that workers will benefit from training and re-employment opportunities.[159] Just Transition Agreements were created as a tool that focuses on projects at the regional and local level.[160]

Mandating that renewable energy project developers employ a certain share of the local population in jobs requiring all skillsets (from low-skilled to high-skilled labour) can create local employment and capture value locally. Requiring that a portion of renewable energy projects have local ownership or use local components and provide financial benefits to local communities also can aid distributive justice (► see Sidebar 7).[161] Such broader socio-economic benefits of renewables can be built on by involving domestic firms and businesses in a competitive manner aimed at job creation, skills and knowledge transfer; and by involving local communities in the implementation of broader renewable energy targets.[162]

Adjusting international trade treaties can allow more space for developing countries to create domestic renewable energy industries or services, such as local assembling, installing, and maintenance, enabling countries to move beyond only raw material extraction.[163] Such an approach will also impact labour activities, as demands for different types of skills may be affected by reducing trade barriers and opening up opportunities for service industries, for example. Intra-regional South-South trade integration has the potential to support a more equitable and higher uptake of renewables, helping to alleviate asymmetries in trading positions and bolstering the capacity of low-income countries to develop their own markets.[164]

Andy Aitchison / Ashden

Glacier National Park

Sidebar 7. Local Content in Renewable Energy Tenders and Socio-Economic Benefits of the Energy Transition in Uruguay

Between 2006 and 2019, Uruguay transitioned from having a 36% share of renewables in its primary energy mix to having a 63% share. In 2019, renewable energy accounted for nearly all (98%) of the country's electricity supply, including 50% hydropower, 30% wind energy and 15% biomass. At certain times during the year, more than 90% of the electricity consumed in Uruguay was generated from wind energy. A forecasting model (SimSEE) was created to help integrate high shares of variable renewables into the grid.

Uruguay's rapid energy transition was the result of a long-term national strategy that included capacity building at all levels (technical, academic, administrative, etc.). In addition, the country collectively created a new national narrative identifying the benefits of the transition for local development. The strategy's core elements were: 1) a model of "adaptive governance", which includes iterative consultation processes and the anticipation of possible conflict points, and 2) public-private participation mechanisms, where public bodies play a key role in governing public goods while creating clear and transparent conditions for private participation.

Cross-sectoral consultations took place involving energy authorities and several other ministries, such as economy, planning, agriculture, and housing, as well as the Chamber of Industry and workers' unions. Although the Uruguayan utility UTE is a public company, two-thirds of the USD 6 billion invested in the energy transition (from 2012 to 2017) came from private companies.

Following the multi-stakeholder consultation process, a minimum requirement for local content was included in public tenders for long-term PPAs for renewable energy projects. For example, wind farms of between 30 and 50 MW in size had a minimum requirement of 20% local content in the supply value chain and a minimum of 80% local jobs. For biomass, power plants up to 20 MW with at least 30% local content could benefit from a net metering tariff for their reserve capacity of USD 48 per MW per hour of availability. In addition, the first three projects with at least 50% local content received a higher tariff.

As a result, the local content of the PPAs varies from 20% for most wind projects (some of them reaching 45%, for example if the turbine towers are made from concrete), to more than 60% for certain biomass projects and up to 40% for solar energy projects. By contrast, global estimates average 20-25% local content overall. In Uruguay, a total of 50,000 jobs were created in the transition, representing 3% of the country's workforce.

The direct benefits of Uruguay's energy transition are an estimated USD 500 million annually in savings from energy imports (around 1% of GDP). The income from electricity export could reach USD 450 million per year. While it is difficult to quantify the number of jobs maintained since the transition phase, the country now exports its expertise to neighbouring countries, providing capacity building and developing renewable energy projects, which leads to new sources of job creation.

Source: *See endnote 161 for this chapter.*


Adobe Stock

RECOGNITIONAL JUSTICE: RESPECTING HUMAN RIGHTS IN THE ENERGY TRANSITION

Human rights abuses exist across a number of industrial sectors, with nearly 28 million people living under forced labour conditions globally as of 2021.[165] Millions of people worldwide are forced out of their homes and land for large development and business projects; other reported abuses related to diverse economic activities are violations to Indigenous Peoples' rights and attacks on land and environmental defenders.[166] In this context, it is important to consider how the renewable energy sector can both respect and support fundamental human rights.[167]

In addition to the human rights obligations of countries, businesses have a pivotal role in complying with laws and respecting fundamental rights.[168] While governments have the obligation to protect citizens against human rights abuses within their jurisdiction, businesses have the responsibility to "avoid causing or contributing to adverse human rights impacts through their own activities", to "address such impacts when they occur", and to "seek to prevent or mitigate adverse human rights impacts that are directly linked to their operations, products or services, even if they have not contributed to those impacts".[169] Prevention measures include embedding due diligence on human rights into operations, introducing remedies and grievance mechanisms, and ensuring that the opinions and perspectives of all stakeholders are represented fairly[i].[170] Underlying these approaches is the "Leave No One Behind" principle of the United Nations, which calls for eradicating poverty in all its forms, ending discrimination and exclusions, and reducing inequalities[ii].[171]


Luke Metelerkamp / CIF Action


Ashden

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[i] Sector-specific indicators identified in the Renewable Energy and Human Rights benchmark of the Business and Human Rights Resource Centre include Indigenous Peoples' and affected communities' rights, land rights, security and high-risk contexts, rights of environmental defenders, labour, health and safety, rights to a healthy and clean environment, transparency and anti-corruption, as well as equality and inclusion. See endnote 170 for this chapter.

[ii] Leave No One Behind states an "unequivocal commitment of all UN Member States to eradicate poverty in all its forms, end discrimination and exclusion, and reduce the inequalities and vulnerabilities that leave people behind and undermine the potential of individuals and of humanity as a whole". See endnote 171 for this chapter.

HUMAN RIGHTS IN THE FOSSIL FUEL-BASED ENERGY SYSTEM

From the perspective of recognitional justice and human rights, fossil fuel extraction and use has wide-ranging impacts, as does nuclear energy.[172] Not only do these activities cause irreversible harm to local environments and livelihoods, but they also are responsible for violations to land rights and Indigenous Peoples' rights, attacks on rights defenders and increased criminality.

Among recent examples, the East African Crude Oil Pipeline project in Uganda and Tanzania involves drilling in protected natural areas and is jeopardising water resources and threatening the livelihoods of an estimated 100,000 people.[173] On top of irreversible environmental degradation, reported human rights abuses related to the project include land requisition without compensation, the loss of means of subsistence, violation of Indigenous Peoples' rights, destruction of housing, arrests and intimidation of human rights defenders, and arbitrary suspension of non-governmental organisations.[174]

Shale oil and fossil gas fracking activities in North America have involved land grabbing, soil and water pollution, and exposure to health hazards among low-income rural communities and Indigenous Peoples.[175] In Canada, the Fort Nelson First Nation in British Columbia has protested the impacts of shale gas development on the availability and quality of water resources, and the Elsipogtog First Nation in New Brunswick has brought attention to the lack of consultation during gas exploration, leading to violent clashes with authorities.[176] Meanwhile, a coal mine expansion in Germany that will destroy the village of Lützerath has led to the eviction of residents and environmental activists.[177]

> Among recent examples, the East African Crude Oil Pipeline project in Uganda and Tanzania is jeopardising water resources and threatening the livelihoods of an estimated 100,000 people.

The operation of fossil fuel refineries can result in local impacts including the destruction of farmland, abandonment of fishing settlements, and pollution of rivers and estuaries. Meanwhile, pipelines and other supporting infrastructure have contributed to population displacement and resettlement, disputed property valuation and delayed compensation, livelihood disruption, food insecurity, and overall uncertainty, fear and anxiety. [178]

In some cases, such impacts have been heightened by the creation of "man camps" (I.e., temporary housing) for workers in the fossil fuel industry.[179] In the western United States, a 2019 study reported higher criminal activity in the Bakken oil-producing region of North Dakota and Montana, coinciding with socio-economic changes related to the shale oil boom.[180] Between 2006 and 2012, the rate of aggravated assault increased 70% in the region, while falling 8% outside the region.[181] The rate of violent victimisation – including homicide, non-negligent manslaughter, rape and sexual assault, robbery and unlawful attack – increased 30% in the region but fell 4% outside it.[182] Men reported higher rates of violent crime, while women reported a 54% increase in unlawful sexual contact, including statutory rape.[183]

Jerry Chidi / Climate Visuals

HUMAN RIGHTS AND RENEWABLES

Human rights abuses exist across many industrial sectors, particularly in legal contexts where authorities fail to protect these fundamental rights. Allegations of human rights abuses have occurred in several cases in the renewable energy industry as well, with reported abuses including the violation of land rights and the rights of Indigenous Peoples, forced labour, attacks on and murders of environmental defenders, and the displacement of populations.[184] Other key challenges related to renewables include working conditions in the upstream and downstream supply chains and the gender dimension, such as women's access to energy services and representation in labour dynamics. As the industry takes steps to prevent and mitigate these issues, it is important to review them to identify appropriate risk mitigation paths.

Indigenous Peoples' Rights, Local Communities and Land Rights

Status

Indigenous Peoples, as well as local communities including farmers, manage an important share of global forests and agricultural lands, which may be affected by the deployment of large-scale renewable energy projects.[185] The increasing competition for land and resources can result in threats and violations to these rights, including loss of livelihoods and culture.[186]

Indigenous Peoples are on the frontlines of climate change and experience some of its most intense impacts. These climate-related effects will only exacerbate the ongoing impacts that these groups face related to political and economic marginalisation, loss of land and resources, discrimination and unemployment.[187] Many of the world's non-commercially exploited lands and resources are located in Indigenous territories.[188] The UN Declaration on the Rights of Indigenous Peoples emphasises Indigenous Peoples' rights to the "territories and resources which they have traditionally owned" and highlights that "no relocation shall take place without Free, Prior and Informed Consent (FPIC)".[189]

> ✔ The deployment of renewable energy can be tailored and designed to fit diverse contexts and to consider specific characteristics of land, fauna and flora, and cultural heritage.

Benefits

If properly implemented, in contrast to fossil fuels and nuclear energy infrastructure, the deployment of renewable energy can be tailored and designed to fit diverse contexts and to consider specific characteristics of land, fauna and flora, and cultural heritage.[190] Renewables also can provide energy access and economic development for Indigenous Peoples, who are often among the most vulnerable and poor communities.[191]


Land Rover Our Planet

In the United States, six tribes have joined in a wind power project to bring energy self-sufficiency and revenue to tribal lands in the state of South Dakota. By forming a multi-tribal power authority and entering into a joint venture with a wind developer, the tribal authority is able to bring its knowledge and expertise to assess environmental and social aspects, while the wind developer contributes technical and regulatory know-how. The resulting Oceti Sakowin Power Project is expected to provide electricity for the tribes as well as employment and revenue from selling surplus electricity to the grid.[192]

In Canada, around 200 medium- to large-scale renewable energy projects involving Indigenous Peoples were either in operation or in the final stages of planning or construction as of 2023.[193] Most of these projects involve partnerships between Indigenous communities and energy companies, utilities or developers.[194] Meanwhile, the Right Energy Partnership with Indigenous Peoples explicitly focuses on aspects such as community ownership, knowledge exchange and self-determined sustainable development.[195]

Braden Gunem

> The Hydropower Sustainability Standard allows for certification of hydropower projects based on rigorous requirements for resettlement and engagement with Indigenous Peoples, including through the implementation of FPIC.

Challenges

Historically, "modern"[i] states have not taken into account the rights of Indigenous Peoples and have frequently imposed on them value systems rooted in Western cultures.[196] Infringements on Indigenous rights stem from a wide range of economic activities, including the energy industry, with many well-documented examples linked to fossil fuel development.[197]

In the case of renewables, large-scale hydropower development has historically led to negative impacts on the local economy, with effects on the availability of fisheries, on transport, and on water availability and quality (► **see Ecosystems chapter**).[198] The construction of the world's biggest dam, the Three Gorges Dam in China, led to the displacement of 1.3 million people.[199] Estimates suggest that 40 to 80 million people have been displaced due to dam projects worldwide as of 2000. This number accounts for physical displacement and does not consider displacement due to livelihood losses upstream and downstream of dams (**see pp. 140 and 142, and Box 14 on the Hydropower Sustainability Standard**).[200]

Examples of recent controversial wind power projects include the Roan and Storheia wind farms in Norway, the Turkana wind project in Kenya and the Guuna Sicarú wind farm in Mexico.[201] In these countries, national courts ruled that the projects – which had already been built – violated rights (of the Sami people in Norway, local communities in Kenya and the Zapotec people in Mexico).[202]

Box 14. Newly Certified Sustainable Hydropower Projects

In March 2023, Sebzor power plant in Tajikistan became the world's first certified hydropower project, in the "silver" category of the Hydropower Sustainability Standard. The assessment was supported by the Hydropower ESG Assessment Fund (HESG) of the Swiss State Secretariat for Economic Affairs (SECO). The second certification process took place in Quebec, Canada, where the project Eastmain-1 Development obtained the "gold" certification in July 2023.

Source: *See endnote 217 for this chapter.*

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[i] In the sense of modern administrations in contrast to the "legal, institutional and cultural traditions stemming from the cosmovisions of indigenous peoples around the world". See endnote 196 for this chapter.

In Ecuador, a global shortage of balsa wood, used in the blades of wind turbines, reportedly led to unregulated overharvesting in the Amazon basin.[203] To obtain the raw material, industry players offered attractive prices to local Indigenous Peoples – many of whom face conditions of poverty – leading to the degradation and overuse of their lands.[204] Biomass and biofuels can similarly divert resources from local populations, as the land and water requirements of bioenergy feedstocks can lead to a focus on fuel rather than food production.[205] In most cases, it has been argued that the communities affected by these developments do not benefit from the electricity generated.[206]

Risk Mitigation: Solutions and Good Practices

Decision makers in industry, government and elsewhere are increasingly taking steps to address human rights concerns associated with renewables. They are introducing requirements and mechanisms that enhance the transparency of project development and operations and ensure the appropriate involvement of Indigenous Peoples and local communities. At the international level, the United Nations has developed a set of Guiding Principles on Business and Human Rights, and the OECD has developed Guidelines on Responsible Business Conduct for Multinational Enterprises.[207]

Although at present there is no explicit reference to a general human right to land in international human rights law, a number of international human rights instruments do link land issues to specific fundamental rights. For example, references to land are made in relation to the right to food, gender equality, and protection and assistance to internally displaced persons.[208] In the case of Indigenous Peoples, the rights to their lands, territories and resources are explicitly recognised in the United Nations Declaration of Indigenous Peoples' rights.[209]

Best practices available to companies include developing management systems that account for human rights and land rights, requesting ESG advice, integrating human rights due diligence into supply chain contracts and strengthening risk assessments related to human rights. Underlying these best practices is the advanced design and implementation of Strategic Environmental Assessments (SEAs) and Environmental, Social and/or Human Rights Impact Assessments (ESHIAs), combined with mandatory human rights and environmental due diligence (mHREDD) to ensure that human rights and land rights are respected.[210] Another relevant framework is the principle of legitimate tenure rights, whereby land rights are acknowledged in the absence of formal documentation.[211]

✓

At the international level, the United Nations has developed a set of Guiding Principles on Business and Human Rights.

National Renewable Energy Lab

Any decision to implement a project in a given location should be based on Free, Prior and Informed Consent (FPIC) by local communities, with a focus on Indigenous Peoples, who are often left out of the design of impact assessments and whose consent rarely conforms with FPIC.[212] FPIC reflects a collective decision-making process involving all those who are potentially affected by the outcomes.[213] It is based on voluntary consent free of coercion, which is sought prior to a project's implementation based on objective information provided to those involved. Implementing FPIC by local communities in renewable energy projects can mitigate many of the breaches of rights to property, land, development and self-determination facing Indigenous Peoples and affected communities.[214]

Bolivia and Sierra Leone provide notable examples of adopting FPIC principles in national law. By incorporating the UN Declaration on the Rights of Indigenous Peoples into its national legislation, Bolivia took a substantial step towards protecting the land and resource rights of Indigenous Peoples.[215] Sierra Leone has introduced a law targeting minerals and mining operations, which requires companies to obtain FPIC from communities before starting operations.[216] At the international industry level, the Hydropower Sustainability Council launched a Hydropower Sustainability Standard in 2021 that allows for certification of hydropower projects based on rigorous requirements for resettlement and engagement with Indigenous Peoples, including through the implementation of FPIC. The Hydropower Sustainability Standard is now managed by the Hydropower Sustainability Alliance (HSA) (► see Box 14, p. 138).[217]

Effective participation of Indigenous Peoples in national energy transformation plans can ensure that later industry developments integrate their knowledge and views from the outset.[218] For example, a note by the UN Permanent Forum on Indigenous Issues emphasises the benefits of sharing "their holistic and comprehensive views on issues related to the energy mix" in global decision-making contexts.[219]

✓

> Any decision to implement a project in a given location should be based on Free, Prior and Informed Consent (FPIC) by local communities, with a focus on Indigenous Peoples.


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Adobe Stock


Dept of Energy Solar Decathlon / US Department of Energy


Lamine Coulibaly / CIF Action

Renewables, Forced Labour and Working Conditions

Status

In 2021, an estimated 27.6 million people were victims of forced labour worldwide, across all economic sectors.[220] According to the International Labour Organization, violations of international labour standards in global supply chains are related to shortcomings in legislation, enforcement and access to justice in different regions.[221]

Challenges

The increasingly global nature of renewable energy supply chains introduces risks for the sustainability of renewables, as traceability remains a challenge in global upstream and downstream supply chains.[222] This challenge is increased by the fact that many jobs are found in the informal sector, such as for biofuels (especially cultivation), mining and discarded e-waste.[223]

Concerns about working conditions and especially forced labour in the renewable energy supply chain have come to the forefront in recent years.[224] In the case of solar PV, the initial steps of manufacturing include the mining of silicon dioxide, which is transformed into polysilicon for use in modules through a chemical purification process. As much as one-third of the world's polysilicon supply comes from companies active in Xinjiang province, China; several organisations, such as the US Department of Labor, the Business & Human Rights Resource Centre (BHRRC), and Sheffield Hallam University, highlighted such companies' potential implication in state-sponsored forced labour involving the Uighur population.[225] In response, regulators in key polysilicon markets such as the United States and the EU have pressured manufacturers to set more stringent requirements on the human rights records of their suppliers.[226] Chinese authorities have denied the forced labour claims, although a UN Special Rapporteur on Contemporary Forms of Slavery found them "reasonably likely".[227]

Box 15. Solar Stewardship Initiative

In 2022, the industry associations SolarPower Europe and Solar Energy UK initiated the Solar Stewardship Initiative (SSI), aimed at promoting responsible production in the solar energy value chain. The initiative, building on the sustainability work carried out since 2015, brings together more than 60 organisations including manufacturers, developers, installers and purchasers and seeks to increase the transparency of the solar value chain to ensure that the highest environmental, human rights and governance (ESG) standards are respected and that forced labour is banned along the supply chain.

In October 2023, following a pilot and a public stakeholder consultation, the SSI published its ESG Standard, which will be complemented by a Supply Chain Traceability Standard in 2024. The SSI will ensure companies' compliance with the ESG Standard through third-party verification. Multi-stakeholder participation in the SSI governance and a Complaints & Appeal mechanism ensure accountability and the credibility of the scheme. The roll-out of the SSI Assurance Scheme was to begin in December 2023 with the first certification audits expected in Q3 2024.

Source: *See endnote 236 for this chapter.*

Allegations of forced labour and poor working conditions also have been reported on Brazilian sugar plantations.[228] However, Brazilian studies highlighting the socio-economic benefits of sugarcane production suggest that the modernisation of sugarcane harvesting (i.e., banning the practice of pre-harvest burning and switching to mechanical harvesting), together with stricter compliance with international labour standards, have ensured that these situations are now the rare exception.[229]

Concerns also have been raised about the use in many countries of forced and child labour in the mining industry, which extracts the minerals needed to build renewable energy and electric mobility technologies (► see Materials chapter).

Risk Mitigation: Solutions and Good Practices

The respect for human rights around working conditions is related to policies and good practices that encourage and enforce human rights more broadly. Public policy and government regulation that requires mandatory due diligence on human rights (mHREDD) can ensure that companies embrace their responsibility to identify and mitigate human rights issues in their supply chains and support workers affected by extractive industries. The EU's Corporate Sustainability Reporting Directive mandates the disclosure of sustainability impacts of around 50,000 companies, and the French Duty of Vigilance Law requires companies to draft a statement on their human rights record throughout their supply chain.[230]

According to the Corporate Human Rights Benchmark of the World Benchmarking Alliance, the absence of such mandatory measures has resulted in almost half of the world's largest companies (from all sectors) not showing evidence of identifying or mitigating any type of human rights issue in their supply chains.[231] Adapting and implementing human rights standards is often based on the available capacity of local governments, especially in low-income countries where capacity transfer in the form of know-how can help in designing and implementing such policies.[232]

Investors have a significant role to play not only in providing capital flows to renewable energy but in raising the bar on human rights in the sector. The multitude of issues resulting from lengthy supply chains, limited mineral resources and untransparent labour relations have brought to light the vexing challenge of directing investment to the right places.

To this end, the BHRRC has assembled a practical guide for investors and policy makers towards driving a just transition.[233] The guide highlights best practices such as: active stewardship by investors and responsible investment policies, including voting and proxy resolution guidelines; building renewable energy investment practices that respect human rights; maximising leverage by actively engaging with renewable energy investors; driving collective action such as the Advance initiative from Principles for Responsible Investment (PRI), which engages renewable energy companies on human rights; and engaging governments and standard setters to adopt national policy to protect human rights.[234]

Multi-stakeholder platforms can encourage greater transparency and a better understanding of issues faced by workers and the industry, and ensure equitable outcomes. The voting procedures of the Initiative for Responsible Mining Assurance involve equitable representation of civil society, communities, organised labour and the private sector (► see Materials chapter).[235] Similarly, the Solar Stewardship Initiative works with manufacturers, installers, purchasers and developers across the value chain to foster responsible production and sourcing of materials (► see Box 15).[236] Its aims include establishing mechanisms that ensure the integrity of the industry as a whole, creating transparency in supply chains (through due diligence and disclosure) and preparing the industry for upcoming legislation.[237]

Involving a diverse set of stakeholders (including civil society) in decision making can enhance both environmental protection and human rights in renewable energy projects.[238] The Hydropower Sustainability Standard aims to ensure good practice in project preparation, implementation and operation by driving multi-stakeholder engagement and ensuring transparent processes.[239] Assessments under the Standard use data triangulation, comparing project documents to site visit photos and interviews with affected communities; this ensures that affected stakeholders are built into the decision-making processes and are able to provide their input in a participatory and transparent manner.[240] Certain stakeholders have undertaken efforts to outline a vision for a sustainable hydropower industry capable of contributing to climate and development goals.[241]

✓

Involvement of a diverse set of stakeholders (including civil society) in decision making can enhance both environmental protection and human rights in renewable energy projects.

The 2021 World Hydropower Congress facilitated a multi-stakeholder public consultation process to develop the San José Declaration on Sustainable Hydropower, which outlines principles for the sustainable use and planning of hydropower stations.[242] These include: delivering ongoing benefits to communities, livelihoods and climate; only accepting sustainable hydropower[i]; and ensuring that stakeholders work together.[243] The declaration provides explicit recommendations for decision makers, such as: gathering information on needs and opportunities, incentivising sustainability in the sector, deciding who is to pay for reliable renewable energy systems, upgrading existing infrastructure, exploring options for dams that no longer provide sufficient benefits to be either enhanced with additional services or decommissioned ("use it or lose it" principle), and advancing river restoration.[244]

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[i] The definition of "sustainable hydropower" under the San José declaration underlines that the preparation, implementation and operation of hydropower should be delivered in accordance with international good practice as defined by the Hydropower Sustainability Standard, according to a set of principles and recommendations. See endnote 243 for this chapter.


Gaganjit Singh / UN Women

Gender Equality

A just energy transition means ensuring that the opportunities being created benefit all people, are accessible to all and are distributed equally.[245] A focus on a gender-just energy transition takes into account the differences in how women and men engage in, access and use energy services and the opportunities that they provide.[246]

Status

Energy access context

The availability of gender-disaggregated data within the energy context is limited.[247] However, a handful of studies highlight that the impacts of climate change mainly affect women and girls in developing countries, that women and girls are more exposed to health risks due to indoor air pollution from inefficient cook stoves, and that energy poverty affects women more than men.[248] These outcomes are attributed to women's social roles and responsibilities in society and to their limited access to productive resources (such as financial resources, land, capacity building programmes and education), among other factors. Adopting a gender mainstreaming approach[i] to overcome challenges that are faced mainly by women can lead to a more gender-equal energy transition.[249]

Employment context

Studies show that, for any type of industry, greater gender equality can drive productivity and growth in that industry. A 2015 report suggested that if all countries advanced women's equality to match the progress of their regional leaders, as much as USD 12 trillion could be added to global annual GDP by 2025, relative to business-as-usual.[250] This is because gender-equal workplaces tend to enhance productivity and creativity, resulting in higher revenue, better employee engagement, more diverse cultural insights and knowledge, broader skillsets and decreased employee turnover.[251]

✓ Globally, the renewables industry outperforms the traditional energy industry in female employment, with 32% of the workforce being women.

The energy industry overall is male-dominated, with women comprising only 22% of the workforce as of 2018 and earning on average 19% less than men, one of the largest gender wage gaps globally.[252] The gap tends to be wider for high-skilled workers and is mainly found within, as opposed to between, companies.[253] The oil and gas industry workforce comprises only 22% women, and the wind industry employs 21% women, whereas the solar industry employs 40% women – nearly double the share of the energy industry as a whole (► **see Figure 33**).[254] This illustrates how the renewable energy industry has, in general, a better gender balance than the energy industry as a whole. Globally, the renewables industry outperforms the traditional energy industry in female employment, with 32% of the workforce being women.[255]

Even where women have managed to find employment in the energy sector, they tend to work in administrative and support functions rather than managerial roles. This is the case in both the renewable and non-renewable energy industries. For example, in the solar PV industry, women account for 58% of the administrative jobs globally, yet they hold only 30% of managerial jobs and less than 13% of senior management positions.[256]

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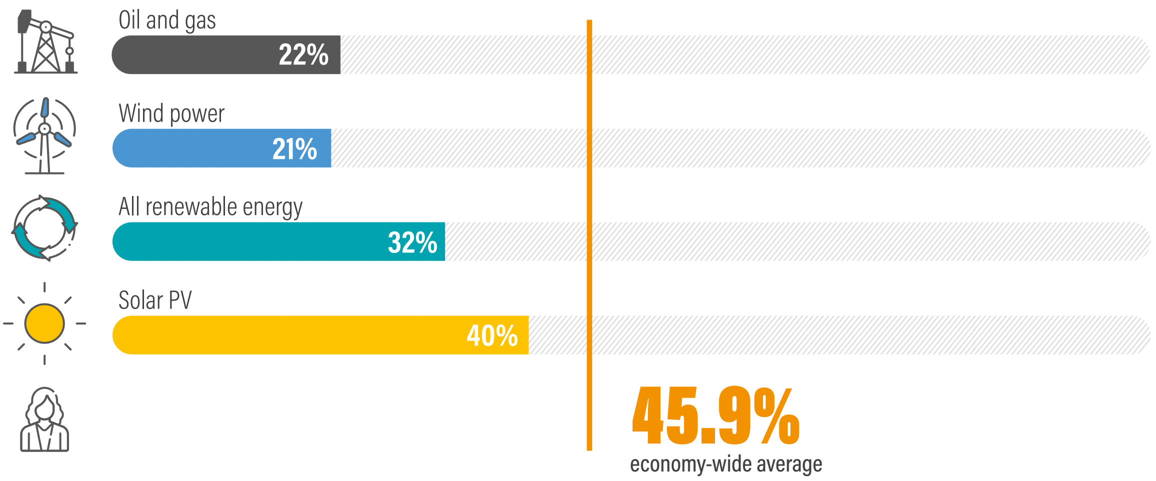
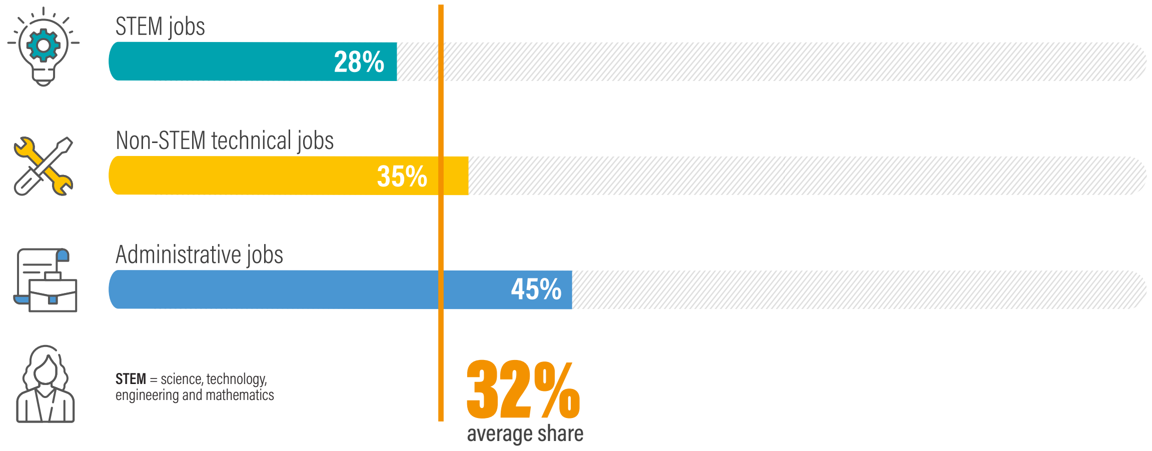
[i] Gender mainstreaming is the inter-governmentally agreed, global strategy for achieving the goal of gender equality. It is defined by the UN Economic and Social Council as: "the process of assessing the implications for women and men of any planned action, including legislation, policies or programmes, in all areas and at all levels". See endnote 249 for this chapter.

FIGURE 33. Share of Women's Employment by Energy Sector, 2021



Source: *IRENA. See endnote 254 for this chapter.*

FIGURE 34. Share of Women's Employment in Renewable Energy, by Type, 2018



Source: *IRENA. See endnote 258 for this chapter.*

The underrepresentation of women in highly technical positions in the energy sector is reflective of a larger societal-level problem where women generally are not strongly represented in science, technology, engineering and mathematics (STEM) positions, representing just 32% of total employment in these fields.[257] This underrepresentation of women in STEM positions is similar in the renewable energy industry, where women accounted for only 28% of the STEM workforce in 2018 (► see Figure 34).[258]

Challenges

Energy access context

In the pursuit of energy access, women face critical obstacles. Cultural norms limit their involvement in the energy field due to gendered labour divisions. Moreover, access to information, skills, training and labour markets remains unequal. Gender-sensitive policies are still limited, and training opportunities are often biased.[259] In lower-income countries in particular, enterprises that employ women are frequently part of the informal sector; women-led businesses are often home-based and tend to be excluded from energy intervention projects.[260] Addressing these challenges is vital for achieving gender equity in the energy access context.

Employment context

The obstacles that women face in accessing energy sector employment are multifaceted and are entrenched in societal, cultural and organisational structures. Traditional gender roles, STEM-related stereotypes, unconscious bias during recruitment and a lack of clear gender diversity goals within companies and institutions often discourage or even prevent women from pursuing energy careers.[261] Lack of awareness about career options compounds this issue. Workplace challenges, such as inadequate maternity leave and inflexible hours, discourage women from pursuing or staying in renewable energy careers.

Societal expectations and limited mobility also affect women's career progression, especially in remote areas. Glass ceilings[i], gender bias, and unequal mentorship and leadership opportunities often limit women's progress after entry. Persistent

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[i] The glass ceiling is defined as "an intangible barrier within a hierarchy that prevents women or minorities from obtaining upper-level positions", from Merriam-Webster, https://www.merriam-webster.com/dictionary/glass%20ceiling.

Box 16. Distributed Renewables for the Empowerment of Women

Distributed renewable energy solutions have the potential not only to provide access to clean and reliable energy, but also to empower women in local communities to drive this development.

Barefoot College International is a women-centred global network that operates in 93 countries across the Americas, Africa, Asia and the Pacific Islands. Through local centres, Barefoot College offers illiterate and semi-literate women training opportunities that focus on self-advocacy and resilience. One of its programmes, Solar Mama, trains women over the course of six months to assemble, install, maintain, and operate solar equipment, including solar lanterns, lamps, parabolic cookers, water heaters and other devices. The trained women return to their villages with the equipment and necessary knowledge to deliver off-grid renewable energy solutions to their communities. So far, Solar Mama has trained more than 3,500 women and provided over 175,000 installed solar systems.

Green Girls Organisation uses artificial intelligence to determine the specific energy needs of African rural communities and, in turn, provides tailored clean energy solutions to those who do not have access to clean and affordable energy. Through its Green Women Empowerment Programme, Green Girls Organisation trains rural women on how to build and sell solar lamps, install and maintain solar panels, and construct and operate biodigesters for biogas production used for cooking and organic fertilisers. Additionally, through 48 Green Girls Clubs, girls aged 14-19 can learn about climate change and action. Green Girls Organisation has reached 68 villages across Cameroon, the Central African Republic, and the Democratic Republic of Congo, and is also launching programmes in the Gambia, Mali, Niger, Nigeria and Senegal. More than 1,300 and 3,000 women have benefited from the Green Empowerment Programme and the Green Girls Clubs, respectively.

Source: *See endnote 263 for this chapter.*

pay disparities exist, with women typically earning less than men in similar roles, necessitating action for pay equity. Addressing these challenges is essential for creating a more inclusive and equitable modern energy access landscape.[262]

Solutions and Good Practices

Energy access context

Increasingly, women are becoming active agents in the deployment of off-grid renewable energy solutions, which has been shown to improve sustainability and advance gender equality (► see Box 16).[263] To scale this trend, a multi-faceted approach is essential, including facilitating access to technical, business, and leadership training for women, and encouraging women's entrepreneurship within the energy sector.[264] Ensuring that women have equal access to financial resources can guarantee their participation in energy access ventures. Additionally, fostering co-operation with sectors such as health and education can help to empower women on a broader level.[265]

Employment context

A number of good practices are available to advance gender equality in the renewable energy sector, most of which are targeted at helping companies and regulators enhance retention and career advancement of women in the workforce. Investment in STEM education could ease disparities by alleviating the underlying structural issues that often bar women's entry into high-skilled jobs as well as leadership positions. In addition, setting out policies that stipulate maternity and paternity leave, flexible working hours, on-site childcare, gender-specific targets, training and mentoring, and part-time employment all carry potential to enhance the gender balance of the renewable energy industry and foster an environment where women can progress in their careers.[266]


Abbie Trayler-Smith / UK Department for International Development

At the national and institutional levels, there is growing recognition of the feasibility and importance of gender mainstreaming, which involves integrating a gender perspective into energy programmes and the overall development agenda to effectively address the distinct needs of women.[267] The International Labour Organization has outlined strategies towards gender equality and mainstreaming, incorporating a gender lens in all of its work for the past two decades.[268] This approach has cascaded into enhancing the accessibility of technologies and support services for women-led enterprises, including through earmarked funding, tailored advice and collection of gender-disaggregated data.[269]

Intergovernmental organisations such as IRENA have suggested that introducing numerical quotas or targets can help enhance the representation of women.[270] In addition to sectoral initiatives, organisations such as the Global Women's Network for the Energy Transition (GWNET) propose mentorship, training and knowledge-sharing activities and advocate to address gender imbalances in the energy sector and to promote gender-sensitive actions related to the energy transition.[271]

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Increasingly, women are becoming active agents in the deployment of off-grid renewable energy solutions.

PROCEDURAL JUSTICE: CITIZENS' PARTICIPATION AND OWNERSHIP

A third thematic approach to energy justice is "procedural justice", which focuses on access to decision-making processes and how decision makers engage with citizens.[272] Studies amply illustrate that procedural engagement of communities can contribute to greater support for new technologies, including renewables.[273] Energy justice relates to citizens' active participation in the energy transition, resulting in energy democracy. It entails more direct control of shared energy assets by those who use them on a day-to-day basis (► see Special Focus 4, p. 154).[274] Ultimately, energy citizenship involves the institutionalisation of collective decision making in energy systems.[275]

Status

Until recently, citizens have been positioned mainly as consumers of energy, provided that they have access to energy supplies. This reflects in part the historical development of power grids and the emergence of large fossil fuel and nuclear power plants.[276] The earliest power grids of the 19th century were developed at the local scale, to support public lighting and eventually the use of small household appliances.[277] However, as industrial electrification expanded and the need for electricity grew in the late 20th century, this led to a shift towards centralised production and extensive grid systems.[278] Citizens typically were not included in decisions about energy generation and distribution.[279]

In contrast, renewables allow for decentralising and democratising energy generation, raising the possibility of meaningful citizen participation. This has created a setting ripe for energy consumers who also are energy producers ("prosumers").[280] Citizens now have opportunities to participate in energy markets in diverse ways, from municipalities gaining ownership over their distribution grids to communities setting up their own energy generation activities (provided regulations and economic conditions allow for this).[281]

Benefits

Engaging citizens carries a number of benefits, such as increasing the support for new energy infrastructure and distributing financial benefits to communities located near to and affected by energy projects. This includes people previously

✓ Decision makers can mandate a minimum level of citizen participation and ownership of new renewable energy plants.

Jessica Reeder / BlackRockSolar

excluded from decision-making processes who can bring fresh perspectives to the discussion and ensure that policies are implemented effectively, therefore increasing their perceived legitimacy. Engaging citizens also can benefit society in broader terms and enhance the success of the Paris Agreement.[282]

Types of Citizen Participation

Citizen participation can take multiple forms. This can range from playing a central role in the energy market to active participation in policy formulation.[283]

Consumer choice models are a result of the liberalisation dynamic that has emerged in the energy sector in recent decades. According to this logic, consumers have the opportunity to exercise choice when deciding on utility providers. The general interest in buying and investing in renewables at the household and individual levels has brought new opportunities. These include green tariff programmes, which give consumers the option to purchase renewable power under guarantee-of-origin rules; pay-as-you-go services, which enable less-developed grids to incorporate solar PV under use-based purchasing arrangements; and peer-to-peer energy trading programmes, which allow citizens and businesses to directly exchange energy (and related services) without involving a utility (► see Box 13, p. 125).[284]

Microgrids bring added resilience to a locality through a more stable electricity supply that is less affected by load shedding. Despite being self-sufficient energy systems, microgrids encompass all the usual actors and function as a regular integrated power grid, albeit at a smaller scale through a controlling entity. Due to their size and nature, microgrids are located close to citizens and hence can enhance the connection between citizens and the energy system. They also can provide a viable solution for renewable energy access.[285]

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Renewables allow for decentralising and democratising energy generation, raising the possibility of meaningful citizen participation.

The market for microgrids is projected to exceed USD 30 billion by 2027.[286] Examples of successful renewable energy microgrids include Simris in Sweden and Blue Lake Rancheria in the United States.[287] The energy from the Simris microgrid is produced locally by a wind turbine and a solar PV farm, and a central battery system and back-up biodiesel generator also enable the system to operate in island mode.[288] The Blue Lake Rancheria microgrid relies on a PV power plant and battery storage that can both operate in island mode, providing affordable electricity to the local community as well as critical back-up in emergency situations.[289] Factors behind these successes include prior community acceptance of renewable energy installations, a strong mix of relevant actors, as well as incentive schemes from policy makers driving the uptake of a novel solution.[290]

Citizens also can engage in the energy system through **participatory decision making**. Tools that can meaningfully engage citizens include: deliberative events, such as the Citizens Convention for the Climate in France; participatory budgeting, where citizens can contribute to allocating (municipal) budgets; citizen science, where citizens participate in data collection to further understandings on energy-related research; and systematic community engagement, which amplifies the voices of the most vulnerable and most affected who traditionally do not contribute to discussions on the energy transition.[291]


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Another increasingly common pathway is **energy communities**, which typically organise members on a co-operative basis around several key principles.[292] These can include: voluntary and open membership; democratic member control; member economic participation; autonomy and independence; education, training and information; co-operation among co-operatives; and concern for community.[293]

Many energy communities were born from resistance to various developments in the energy arena, mainly in Western Europe. Waves of communities were founded in response to the oil crises of the second half of the 20th century as well as to the two nuclear disasters of Chernobyl and Fukushima.[294] The EU recently strengthened its support for energy communities by formally defining them in two significant pieces of legislation: the Renewable Energy Directive and the Internal Electricity Market Directive.[295]

As regulatory actions for energy communities progress, primarily in developed countries and particularly in the EU, there is an increasing effort to explore the feasibility of these models in developing countries, sometimes also involving Indigenous Peoples (► see Recognitional Justice section). In South Africa's Kwazakhele Township, the Saltuba Community Primary Cooperative empowers residents to leverage existing land and infrastructure for generating income and fostering sustainable livelihoods, encompassing activities such as harvesting rainwater from residential roofs, cultivating vegetables on available land, and selling electricity produced by distributed solar PV panels integrated into the local grid.[296] Everyone is an equal member of the co-operative and has an equal say on how the resources are used.[297]


Ryan Brown / UN Women

In Peru, La Tortuga is setting up an energy community based around a new wind turbine.[298] In Brazil and Mexico, pilot projects are aimed at replicating the co-operative approach to energy governance.[299] Meanwhile, the Philippines is urging community development of micro-grids with the twin aims of reaching 100% electrification and capitalising on a community-driven approach to renewables.[300]

In addition to community energy initiatives, community involvement in the energy transition is growing more broadly. Examples exist of communities purchasing shares in renewable energy companies and of the proliferation of co-ownership and community equity models.

Challenges

The shift towards decentralisation and democratisation of the energy system has been met with resistance, particularly from incumbent companies and public authorities that profit from the status quo.[301] Large fossil fuel producers and utilities have often acted based on their vested interests to slow the energy transition, for example by impeding citizens from participating in energy generation and governance.[302]

Citizen engagement in energy initiatives faces substantial challenges due to inadequate policy frameworks and unfavourable market conditions.[303] The regulatory frameworks of traditional energy markets were designed in the context of centralised, large-scale energy production.[304] As a consequence, alternative frameworks for effective citizen consultation and involvement in energy transition plans are not widespread, and citizens may lack formal avenues to express their views, concerns and preferences in energy transition endeavours.[305]

Policy makers in many regions often overlook the potential of community energy, which can result in policies that do not support or even disadvantage such efforts. Despite recent improvements in the EU, persistent regulatory hurdles include: difficulties in establishing legal renewable energy communities; insufficient incentives for collaborative self-consumer projects; as well as reductions in existing incentives that support small-scale community projects, such as feed-in tariffs.[306] In France, a 2017 regulation change discouraged small projects, prompting community associations to focus on larger, less accessible ventures.[307]

Complex regulatory and administrative hurdles associated with launching new projects pose a significant challenge.[308] Obtaining planning permissions and permits and handling extensive paperwork can require substantial financial resources and expertise, which often is lacking among the volunteer participants involved in community energy projects. The need to develop robust business and financial plans adds to the complexity.[309] In addition, distribution system operators might not acknowledge community energy set-ups as suppliers to the grid, or might prioritise other energy sources.[310]

Another significant challenge facing energy communities is financial, given the substantial upfront investment typically necessary for renewable energy projects.[311] If community members cannot raise these funds internally, external financing becomes essential, whether in the form of grants, bank loans, leasing models or crowdfunding. However, the limited awareness among many banks and financial intermediaries regarding community energy structures can make it difficult for developers to persuade these financiers of an investment's business viability.[312]

The lack of finance is even more persistent in low-income countries. Findings from Sub-Saharan Africa indicate that only a minority of energy projects align with European energy community characteristics, with most local communities lacking the resources to establish and manage their own initiatives.[313]

Solutions and Good Practices

Mechanisms exist at various levels to advance the engagement of citizens in the energy transition. At the supra-national level, the most robust drive for such engagement has been in the EU. The EU has introduced landmark legislation that obliges Member States to transpose definitions and the legal framings of energy communities. Under the European Solar Rooftops Initiative, part of the EU Solar Energy Strategy, all municipalities with more than 10,000 inhabitants should have at least one energy community in place by 2025.[314] The EU also is a substantial funder of research and innovation projects, including the funding of collective action research programmes involving new technologies and citizen engagement elements.[315] Such projects tend to focus on citizen participation in the short term and on general behavioural change in the long term.[316]

Participatory processes also exist at the EU level to involve civil society organisations in energy and grid planning, such as the consultation process of the Ten Years Network Development Plan (TYNDP) of the association of energy transmission operators for both electricity and gas (ENTSOe and ENTSOg). This enables civil society stakeholders to offer their insights and contributions to the planning efforts.[317]

At the national level, the clearest vehicle available for participation is through regulatory frameworks. Beyond adopting general targets for renewables, decision makers can mandate a minimum level of citizen participation and ownership of new renewable energy plants. Examples include the Danish Act on the promotion of renewable energy, which mandates that renewable plants be owned at least 20% by citizens; the Irish Renewable Electricity Support Scheme, which requires a portion of ownership to lie with communities (► see Box 17); and the Dutch climate law of 2019, which aims for 50% local ownership of renewable energy assets by 2030.[318]

Box 17. Ireland's Renewable Electricity Support Scheme

In 2018, the Irish government ratified the high-level design of the Renewable Electricity Support Scheme (RESS). The RESS is in line with the government's climate action goals and aims to promote rural and social development, enhance capacity building and increase the diversity of renewable technologies. It is designed to strengthen community participation and ownership in energy projects, with the goal to have renewables generate at least 70% of electricity by 2030.

According to the targets set out in Ireland's National Energy and Climate Plan (NECP), RESS auctions will be published at regular time intervals throughout the lifetime of the scheme. As of 2020, seven energy community projects had been supported, all in the first auction round.

Eligible projects must apply in conjunction with a Sustainable Energy Community that holds 100% ownership for a project size ranging between 0.5 and 5 MW. Additionally, a community benefit fund set at EUR 2 (USD 2.2) per MWh must be used to support economic, environmental and social development of the local surrounding community. The community benefit funds under the first RESS auction round account for EUR 4 million (USD 4.4 million) per year supporting sustainable community initiatives.

Source: *See endnote 318 for this chapter.*

Regional strategies also can help shape citizen engagement. They can balance the needs of local economies, industries and urban areas while developing specific-enough vehicles for engaging citizens directly. Regional approaches can help harmonise activities across other jurisdictional boundaries. The Dutch Regional Energy Strategy framework established energy regions that cross boundaries of provinces and localities.[319]

Local-level citizen engagement mainly takes shape in participatory processes at the municipal scale. While such participation is standard practice for most Western municipalities, manifested to varying degrees, it often takes the form of mere consultation or simply a sharing of information with citizens rather than active engagement.[320] This is similar with renewable energy projects, where the substantial pushback that is emerging (for example, with anti-wind turbine movements) is attributed to a lack of democratic legitimacy of these projects.[321]

Increasingly, local authorities recognise the value of engaging citizens as a means to achieve multiple goals, such as ending questionable activities by private sector actors, regaining control over local resources, providing affordable services and implementing more ambitious climate targets (► see Sidebar 8).[322]

Sidebar 8. Local Authorities and Citizens' Participation in the Energy Transition

Local authorities can support citizens' participation in the energy transition in many ways, from the early planning stage (through participatory processes in local climate and energy plans) to the operation of municipal or community-led utilities. Local policy makers can set renewable energy targets, mandate shares of local ownership of energy assets and support community energy through public procurement.

Municipalities also can support community energy by providing financial, legal or administrative support; establishing dedicated bodies and one-stop shops; and facilitating interactions with energy utilities and network operators. They can provide access to public spaces and buildings to host community energy projects and map the potential for renewable energy by establishing solar atlases, for example. Local energy agencies also can engage with vulnerable citizens, co-designing strategies to address energy poverty and improve energy efficiency.

These are just a few examples of local authorities' enormous potential to foster the energy transition and the numerous benefits of renewables. For further details, see REN21's *Renewables in Cities Global Status Report*, https://www.ren21.net/cities-2021.

Source: *See endnote 322 for this chapter.*


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Cities can engage citizens in energy policy through (re)municipalisation, or the (re)gaining of control of certain services or assets by a municipality and its citizens. Efforts to remunicipalise power grids have been remarkably successful, especially in Germany (► see Special Focus 4, p. 154).[323] Local (re)purchases of power grids have brought greater transparency to decision-making processes and enhanced citizen involvement in these processes.[324]

Mixing energy generation functions with other economic activities can enhance the participation of communities and the democratic legitimacy of renewables. In particular, using land for agrivoltaic production by combining agriculture and the generation of energy can help to capture value locally and therefore increase citizens' ability to participate.[325] To address challenges associated with accessing distribution infrastructure, including the electric grid, policy makers can enact regulations to ensure low-cost and simple processes that apply specifically to community-led projects.[326]

A major strength of community initiatives is their capacity to engage with each other. In doing so, they can transfer learnings and best practices and help newcomers develop initiatives without having to reinvent the wheel. Ways to increase citizen participation in the energy transition through capacity building include tapping into existing networks of energy co-operatives such as the European Federation of Energy Cooperatives REScoop; joining networks of cities active in the field, such as Energy Cities or ICLEI–Local Governments for Sustainability; and partnering with other social organisations.[327]

Governments can support citizen-led initiatives to overcome challenges of limited capacity and to share best practices.[328] The Sustainable Energy Authority of Ireland has established various initiatives to support public participation in the energy transition and to mitigate these capacity challenges. The most significant, the Sustainable Energy Communities (SEC) network, provides expert support and grants for communities to go through a three-step process of "learn, plan, and do".[329] Another example of sharing best practices is the EU repository of energy communities and its associated rural energy communities advisory hub.[330] The knowledge hubs collect and consolidate data and provide technical assistance to citizens and civil society organisations as well as to policy makers and local businesses.[331]

ADVANCING TOWARDS ENERGY JUSTICE

The energy transition is not simply a technological transition. It carries the opportunity to remedy many of the social and economic challenges associated with a fossil-based energy system.

Using the lens of the three types of energy justice, a focus on the **distribution of costs and benefits** highlights that the financing of renewable energy is not only attainable, but in most cases can be a better investment than fossil fuels. Challenges of energy access and energy poverty can be remedied through the appropriate deployment of renewables and policies targeting energy efficiency, and labour-related issues can be resolved through the expected boom in renewable energy jobs. Focusing on the **recognition of injustices** can help to better understand the major human rights risks that the renewable energy industry faces. Such recognition can help introduce targeted policies and mechanisms to mitigate these risks. Finally, exploring how **participation in energy generation and governance** has been shaped to-date illustrates that the energy transition allows for a growing involvement of citizens, mostly at the local scale. Many potential solutions to the challenges identified exist in light of these three thematic dimensions (► see Table 7).

TABLE 7. Solutions and Good Practices to Advance Energy Justice

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Distributional justice		
Affordability of renewables and access to finance	Public financing	***Examples:*** *General subsidies* *Net metering* *Feed-in tariffs* *Carbon pricing, etc.*
	Sustainable finance	Climate finance ▪ Climate bonds ▪ ESG criteria ▪ Taxonomies ***Examples:*** *Just Energy Transition Partnerships (JETPs)* *Glasgow Financial Alliance for Net Zero (GFANZ)* *Resilience and Sustainability Trust* *International Sustainable Standard Board's Sustainability Disclosure Standards*
	Policy and financial de-risking instruments	Public equity co-investment ▪ Loan guarantees ▪ Political risk insurance
	Just transition action plans and transition taxonomies	***Examples:*** *Just Transition Action Plan of the US state of Colorado* *Just Transition Planning Framework in Scotland*
	Credit and savings co-operatives	***Examples:*** *REScoop MECISE*
Revenues – new and small players	Auction design to reduce barriers and promote participation of small and emerging participants	Project size limitations ▪ Discounted bid bonds ▪ Relaxed qualification requirements ▪ Less-stringent compliance rules
	Emerging equity and business models	Pay-as-you-go ▪ Energy as a service ▪ Co-ownership/co-operative models ▪ Aggregation ▪ Peer-to-peer trading
Energy access	Renewable energy targets for energy access and regulatory frameworks	National and regional (rural electrification) targets and frameworks ***Examples:*** *India's Policy Framework for Decentralised Renewable Energy Livelihood Applications* *Nigeria Integrated Energy Plan*
	Innovative business models	Pay-as-you-go ▪ Energy as a service ▪ Co-ownership/co-operative models ▪ Aggregation ▪ Peer-to-peer trading

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Energy poverty	Energy efficiency and consumption control	Improved insulation, retrofitting, efficient appliances, smart monitoring, behaviour change measures ***Examples:*** *Positive Energy District concept adapted to the historic district of Alfama, Portugal* *Energy Agency of Plovdiv in Bulgaria*
	Renewable energy installations	Offsetting energy costs or generating revenues through net metering or other financing/business models ***Examples:*** *Social housing project of Municipality of Alba Iulia in Romania* *Energy Agency of Plovdiv in Bulgaria installing solar PV panels + storage in social housing* *Energy savings company model in France*
	Public policies targeting vulnerable residents	Social housing retrofits ▪ Trusted energy advice ▪ Energy efficiency campaigns ▪ Sustainable heating systems ▪ Demand-side flexibility measures ▪ Clean mobility options
Jobs and employment in renewable energy	Skills training for renewables	***Examples:*** *South Africa's Renewable Energy Independent Power Producer Procurement Programme* *EU's skills agenda*
	Reskilling specifically for coal workers	***Examples:*** *Just Transition Strategy in Spain* *Romanian Wind Energy Association training schools in coal regions*
	Retraining workers in the oil, gas and auto industries	***Examples:*** *UK's Green Jobs Taskforce* *North Sea Transition Deal*
	Programmes targeting under-represented groups	***Examples:*** *Canada's Student Energy Solutions Movement* *Brazil's RevoluSolar project*
	Mandates for renewables developers	Local job creation ▪ Local ownership ▪ Use of local components ***Examples:*** *Local content requirement in public renewable energy tenders in Uruguay*
	Adjusting international trade treaties	Allowing for domestic development of renewable energy industries and/or services
	Intra-regional South-South trade integration	Alleviating asymmetries in trading positions and enhancing domestic markets

Recognitional justice

Indigenous Peoples' rights, local communities and land rights, ensuring energy access, economic development, and self-determined sustainable development for Indigenous Peoples and local communities	Governance systems accounting for human rights and land rights, based on the United Nations' Guiding Principles on Business and Human Rights	Free, Prior and Informed Consent (FPIC) and the principle of legitimate tenure rights ***Examples:*** *National law in Bolivia including the United Nations Declaration on the Rights of Indigenous Peoples* *National law in Sierra Leone mandating companies to secure FPIC before mining* *Hydropower Sustainability Standard requiring FPIC*
	Community ownership, knowledge exchange and capacity building	***Examples:*** *Oceti Sakowin Power Project in South Dakota, US* *Indigenous Clean Energy Platform in Canada* *Right Energy Partnership with Indigenous Peoples*
	Strong risk assessments	Strategic Environmental Assessments (SEAs) ▪ Environmental, Social and/or Human Rights Impact Assessments (ESHIAs) ▪ Mandatory human rights and environmental due diligence (mHREDD) ***Examples:*** *Hydropower Sustainability Standard* *Solar Stewardship Initiative*

THEME	SOLUTIONS AND GOOD PRACTICES	TOOLS AND EXAMPLES
Renewables, forced labour and working conditions	Public policy and regulations	Mandatory due diligence on human rights (mHREDD) ▪ Adapting and implementing human rights standards ***Examples:*** *EU's Corporate Sustainability Reporting Directive* *French Duty of Vigilance Law*
	Active stewardship by investors	Practical guide for investors and policy makers from the Business and Human Rights Resource Centre (BHRCC) ▪ Advance initiative from Principles for Responsible Investment (PRI)
	Multi-stakeholder platforms	Increased transparency, equitable representation and involvement ***Examples:*** *Initiative for Responsible Mining Assurance* *Solar Stewardship Initiative* *Hydropower Sustainability Standard* *San José Declaration on Sustainable Hydropower*
Gender equality	Enabling and facilitating access to energy and productive resources for women, promoting entrepreneurship skills, and enhancing access to financial resources	Technical, business and leadership training for women ***Examples:*** *Barefoot College International* *Green Girls Organisation*
	Gender mainstreaming	Increasing and enhancing gender mainstreaming initiatives in public and private sectors ▪ Introducing numerical quotas or targets
	Enhancing retention and career advancement for women in the energy workforce	STEM education ▪ Gender-specific targets ▪ Maternity and paternity leave regulations ▪ Flexible working hours ▪ On-site childcare ▪ Part-time employment arrangements
		Training and mentoring opportunities ***Examples:*** *Global Women's Network for the Energy Transition (GWNET)*

Procedural justice

Citizen participation	Encouraging the active involvement of citizens in decision-making processes and local ownership	Enabling regulatory frameworks ***Examples:*** *EU Renewable Energy Directive (definition of energy communities)* *EU Ten Years Network Development Plan (TYNDP)* *Danish Act on the promotion of renewable energy* *Irish Renewable Electricity Support Scheme* *Dutch Climate Law ▪ Dutch Regional Energy Strategy framework* *Citizens Convention for the Climate in France*
	Local authorities engaging citizens in energy development	Early project involvement ▪ Facilitating interactions with energy utilities ▪ Providing financial, legal, technical or administrative support
	Emerging equity and business models	Consumer choice models (e.g., green tariff programmes, pay-as-you-go services, peer-to-peer energy trading) ▪ Microgrids ▪ Energy community initiatives ***Examples:*** *Simris microgrids in Sweden* *Blue Lake Rancheria microgrids in the US* *Saltuba Community Primary Cooperative in Kwazakhele Township, South Africa* *Pilot co-operative projects in Brazil and Mexico (DGRV)* *Energy community in La Tortuga, Peru*
	Facilitating procedures for citizen-led initiatives	Policy makers ensuring low-cost and simple administrative processes that help community-led projects
	Promoting engagement and communication among energy communities; capacity building	Facilitating exchange of knowledge and best practices ***Examples:*** *European Federation of Energy Cooperatives (REScoop)* *Energy Cities ▪ ICLEI-Local Governments for Sustainability* *Sustainable Energy Authority of Ireland* *SEC network ▪ EU repository of energy communities* *Rural energy communities advisory hub*

SPECIAL FOCUS 4. **ENERGY AND ENERGY INFRASTRUCTURE AS COMMON GOODS**

ENERGY SYSTEMS CONSIST of two basic classes of materials: the energy resources themselves (e.g., stocks such as coal, oil and gas; and flows such as wind, solar and geothermal) and the various technological infrastructures used to harvest, transport and distribute these resources to consumers (e.g., oil rigs, solar panels, gas pipelines, electricity grids). Energy resources and infrastructure are subject to differing ownership and control arrangements, which vary across time and space and depend on local historical conditions (e.g., colonial legacies), ideological preferences and external circumstances (e.g., international supply constraints).

What does it mean, then, for energy and energy infrastructure to be common goods? According to one definition, all commons resources share the characteristics of being "jointly used, managed by groups of varying sizes and interests".

In response to Garrett Hardin's "Tragedy of the Commons", Elinor Ostrom famously showed that communities have and continue to sustainably manage common resources successfully by institutionalising self-governed rule systems. To illustrate this, Ostrom drew on examples ranging from irrigation systems in Nepal to lobster fisheries in the United States. She specifically developed her ideas against the dual alternatives of privatisation and state management. However, given recent trends towards privatisation and liberalisation (including in energy systems), sometimes the term "common" is used to refer to public ownership. In this sense, commons are defined mainly in opposition to private and exclusive management and property regimes.

History and Contemporary Relevance

Customary land use rights in England entitled tenants to harvest energy resources from the commons. The rights to harvest firewood were called "estover", and rights to harvest turf for domestic heating were called "turbary"; these rights still exist in some places today, including the United Kingdom and Ireland. Coal resources were largely owned by landowners in European countries; however, they were gradually nationalised in order to rationalise production across fragmented landed property boundaries.

Colonial powers in countries with abundant oil reserves ensured that these resources were essentially under the private control of foreign investors. For example, BP originated in present-day Iran as the Anglo-Persian Oil Company in 1909, operating one such concession system. Independence movements following World War II led to several newly independent countries claiming greater national control over their oil resources, in recognition of their key strategic importance and desire to ensure local benefit.

The United States remains unique in that oil resources belong to private landowners and are not public resources. This aligns with the *ad coelum* doctrine that the landowner's rights extend to heaven and down to hell, thereby including sub-surface resources. With the transition to renewable energy resources such as wind, solar and geothermal, there has been a *de facto* reapplication of this doctrine, as (often private) landowners control who can or cannot use the resource flows above or below their property.

In terms of energy infrastructure, the 20th century saw numerous large-scale, publicly owned energy generation projects. For example, the Shannon hydroelectric scheme played a key role in enabling widespread electrification of Ireland from the 1920s onwards. Public authorities also developed nuclear power stations in several countries. Similarly, for the most part electricity transmission and distribution networks were publicly run throughout the 20th century on a not-for-profit basis. Early Danish adopters of wind energy were local co-operatives that managed the generation infrastructure collectively.

In Western countries, ideological changes following the oil crisis in the 1970s led to a push for electricity sector liberalisation and privatisation. One of the first countries to implement this was Chile in 1982, followed by developed countries. Developing countries have been gradually following the liberalisation model. As of 2016, except in many African countries and the Middle East, most countries in the world had started a liberalisation process, although at different levels. The EU leads this trend, with a completely liberalised market where energy generation transmission and distribution are unbundled, and energy generation is completely open to competition. This liberalisation process also has opened space for new actors to participate in renewable energy generation.

Case Examples and Illustrative Issues

The renewable resource flows being harnessed to power the energy transition – including wind, solar and geothermal energy – are treated as the private assets of landowners rather than as a common resource. This has led some critics to argue for public ownership of the "wind commons" to, in their view, enable a more just and democratic energy transition. Instead of private land markets co-ordinating renewables development, proposed arrangements include state concession tendering systems and community wind rights.

Electricity grid infrastructure has historically been centrally controlled. Even after liberalisation, many states retain strong regulatory powers over transmission and distribution infrastructure. However, technological innovations including microgrid technology bring the possibility for organising electricity production and management collectively as a commons. This could be particularly useful in areas where centralised grid infrastructure is lacking but renewable resources are abundant, such as in sub-Saharan Africa or India.

In the European context, re-municipalisation of energy distribution systems is being hailed as a return to more democratic public control of a common infrastructure. Hundreds of German municipalities have retaken energy systems under public ownership since the mid-2000s. Part of the reasoning behind this movement was the need to support the *Energiewende* (energy transition). Referenda held in Hamburg and Berlin were seen as grassroots, civil society-led social movements to reassert democratic control.

Source: *See endnote 274 for Energy Justice chapter.*

01

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