INNOVATION NODES: INSIGHT REPORT No 2

Renewable energy: emerging technologies and innovations

Collaboration with Harvard Consulting on Business and the Environment

Innovation Nodes at UNICEF Office of Innovation

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Abbreviations and acronyms

a-Si:H	Amorphous silicon
ARENA	Australian Renewable Energy Agency
CdTe	Cadmium telluride
CO_2	Carbon dioxide
CEED	Climate, Energy, Environment, and Disaster Risk Reduction
CHP	Combined heat and power
CIGS	Copper indium gallium selenide
c-Si	Crystalline silicon
CSIRO	Commonwealth Scientific and Industry Research Organization
DER	Distributed energy resources
EV	Electric vehicle
GaAs	Gallium arsenide
GW	Gigawatts
GHG	Greenhouse gas
IEA	International Energy Agency
ILO	International Labour Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelized costs of energy
LICs	Low-income countries
MW	Megawatts
MICs	Middle-income countries
MGA	Miscibility Gaps Alloy
OPVs	Organic PVs
PSCs	Perovskite solar cells
PV	Photovoltaic
PET	Polyethylene terephthalate
PCE	Power conversion efficiency
TES	Thermal Energy Storage
SDGs	Sustainable Development Goals
UNEP	United Nations Environment Programme
UNICEF	United Nations Children’s Fund

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Summary

This report explores the role of renewable energy, in particular solar energy, and emerging solar technologies and innovations to advance energy equity and address the impact of climate change.

Key messages:

- Access to energy is key to human development and wellbeing. But the world is not on track to achieve the Sustainable Development Goal 7 - ensuring access to affordable, reliable, sustainable and modern energy for all.
- A child rights-based approach to clean, affordable and sustainable energy would improve the quality, accessibility and reliability of services such as education, universal healthcare and safe water and sanitation and aid in advancing development goals, reducing multidimensional poverty and lowering emissions that contribute to the climate crisis.
- Our challenge is to provide affordable, reliable and sustainable energy to all and to reduce greenhouse gas emissions and reliance on fossil fuel.
- The energy sector is the major source of greenhouse gas emissions and holds the key to averting the worst effects of climate change. The Intergovernmental Panel on Climate Change Sixth Assessment Synthesis Report asserted that rapid transition to renewable energy is critical to climate resilient development.
- Renewable energy technologies power up multiple SDG results for children, including SGD 1: No poverty, SDG 3: Good health and wellbeing; SDG 4: Quality education; SDG 5: Gender equality; SDG 6: Clean water and sanitation; SDG 7: Affordable and clean energy; SDG 8: Decent work and economic growth, and SDG 13: Climate action.
- The International Energy Agency forecasts solar photovoltaics (PV) and wind will account for nearly 95 per cent of global renewable capacity additions in 2027, with electricity from PV and wind is now cheaper than electricity from fossil fuel in many regions.

- Decentralized energy systems, including off-grid and microgrid systems, are emerging as alternatives to large-scale energy infrastructure to facilitate energy access and resilience in a flexible and adaptable way, especially for communities in Sub-Saharan Africa and South Asia, who experience some of the world's biggest gaps in energy access.
- Solar technologies surpass other sources of renewable energy in terms of their capacity to deliver benefits across different end-use applications and geographical locations and to mitigate climate change. *It is the cleanest, safest and cheapest source of electricity*. *It is adaptable* - solar energy systems can grow as demand and consumption increases, and investment becomes available. *It is affordable* - the establishment and maintenance costs are relatively low compared to other renewable energy sources. *It is durable* - the product lifespan is around 30 years while the lifespan of a wind turbine is about 20 years.
- Solar technologies dominate innovations in the renewable energy sector. The number of patent applications filed for solar photovoltaic (PV) have accelerated in the past decade.
- Most solar cells on the market are based 'first generation' crystalline silicon solar cell technology. The production of these solar cell is complex, with high energy consumption and pollution.
- Third generation solar cells are cheaper to produce than silicon cells. They can be made in a laboratory at scale and have their ability to make electricity that can be 'tuned' by controlling the kinds of molecules that are produced in the manufacturing process. Third generation PV technologies includes perovskite PV, organic PV and quantum dot PV.
- Perovskite PVs are predicted to overtake silicon PV in the solar market in the coming decade. Organic PVs are low-cost and environmentally friendly and can be mass produced at scale using roll-to-roll processing. Quantum dot PV can produce energy with solar and UV light.
- Third generation PV technologies have enabled the development of novel solar innovations such as solar film, solar paint, solar glass, solar skin and solar textile with potential applications for humanitarian situations, post-

conflict and post-disaster recovery and reconstruction, and development settings.

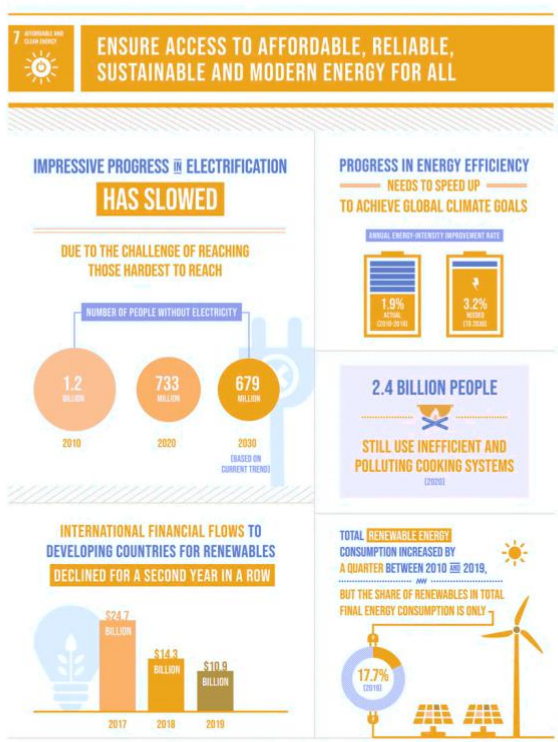
- Energy storage is critical to accelerating the transition of renewable energy. Energy storage solutions must address fluctuation of distributed power sources; enhance the power flow, voltage control and self-recovery capabilities of the distribution network and have long-duration storage and fast response capabilities. Batteries are good for short-duration storage. But a lot of batteries are needed to deliver 8-12 hours of electricity.
- Thermal energy storage technologies, such as the modular Miscibility Gaps Alloy thermal energy storage system, convert electricity to heat and store it until it is needed – hours, days, or months later – by industries/factories, buildings, or even towns.
- The global community needs to identify, minimize and resolve the trade-offs and adverse impacts as the transition to renewable energy accelerates.
- The global community needs to invest in a portfolio of renewable energy innovations across multiple time horizons because better solutions may be available, and what works in the near term may not be effective in the longer term (10 years and beyond) when the conditions for possibility have change.

1. Introduction

Energy lies at the heart of both the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change. The SDG 7 calls to "ensure access to affordable, reliable, sustainable and modern energy for all".

Ensuring access to affordable, reliable, sustainable and modern energy for all will unlock possibilities for millions of people through new economic opportunities and jobs, empowered women, children and youth, better education and health, more sustainable and equitable communities, and greater resilience to climate change. But as Figure 1 illustrates the world is falling short of achieving the targets set for SDG 7 on affordable and clean energy.

Figure 1: Overview of the progress on SDG 7 (2022)



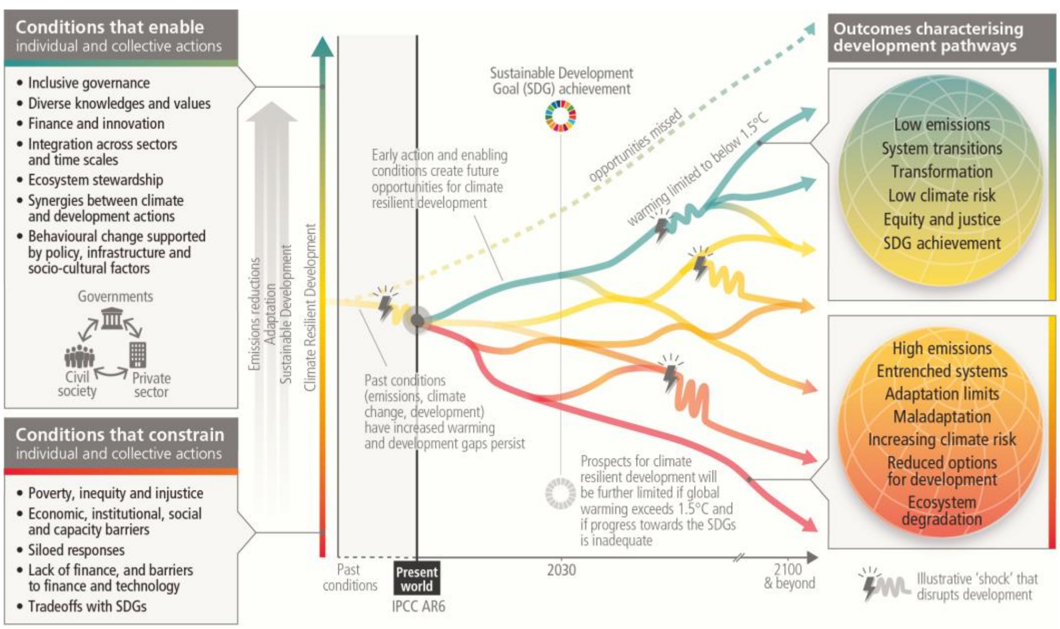
Source: The Sustainable Development Goals Report 2022: https://unstats.un.org/sdgs/report/2022

The Intergovernmental Panel on Climate Change (IPCC)

Human-caused climate change has led to widespread adverse impacts to nature and people. The most affected communities are those who have historically contributed the least to current the climate crisis. The IPCC 2023 Synthesis Report showed proactive adaptation and higher investments can potentially reduce climate risks.[1] Scientists predict with high confidence that major energy system transitions can result in rapid reductions in greenhouse gas emission.[2] Urgent action is needed now. According to the IPCC, options feasible and effective today will become constrained and less effective with increasing climate change.[3] The longer emissions reductions is delayed, the fewer effective adaptation options there will be.

The IPCC's modelling below (Figure 2) illustrates the development pathways (red to green) and associated outcomes (right panel) to secure a liveable and sustainable future for all. The science is clear, the window of opportunity to enable climate resilient development is narrowing rapidly.

Figure 2: Multiple interacting choices and actions can shift development pathways towards sustainability.



Source: IPCC, *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change,* Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 2023 p.61.

Child rights-based approach and child sensitive response

The application of a child rights-based approach to the energy equity requires the full consideration of all children's rights under the Convention on the Rights of the Child and the Optional Protocols.[4] The process of realizing children's rights is as important as the result. From this perspective, access to clean and affordable energy is both a human right itself and necessary for the full enjoyment of a broad range of children's rights such as education, health and wellbeing and clean water.

Virtually every child on earth is affected by climate change, environmental degradation and biodiversity loss. At the same time, where sustainable energy access is lacking or unreliable, children and young people pay the highest price. UNICEF recognizes the connection between equitable access to energy and the realization of child rights and in response, Climate, Energy, Environment, and Disaster Risk Reduction (CEED) are priorities in UNICEF's 2022-2025 Strategic Plan.[5] UNICEF's strategy emphasizes the urgent need to strengthen the services and systems that children need to survive, grow and thrive in the face of climate and environmental threats, including broader disaster risk reduction.

UNICEF's integrated child-sensitive response includes:

- strengthening the resilience and continuity of social services to climate and environmental impacts, including disasters,
- supporting and empowering children and young people to adapt and create a better world,
- advocating with governments and business partners to put children first in their own sustainability plans, budgets and actions towards a green transition,
- building on UNICEF's strengths in innovation to explore, pilot and scale a range of climate and disaster risk mitigation and adaption solutions,
- generating evidence to support decision-making and prioritization, and
- ensuring that the organization embody sustainability within its own global programming, operations, and supply chain.

About this Insight Report

This report explores novel and emerging technologies and innovations in the renewable energy domain with potential to improve energy accessibility and affordability to all in the future, especially underserved, energy-poor communities. The goal is to highlight opportunities to accelerate SDG 7.

Scope

The report explores distributed renewable energy, solar technologies and energy storage because energy transformation and requires changes to energy generation, energy storage and energy infrastructure. We do not explore technologies for deep decarbonisation required to tackle all sources of emissions, not just greenhouse gas, and industrial decarbonization technologies for sectors such as transport, manufacturing, mining, and agriculture.[6] Innovative financing, policy and governance are also out of scope.

Method

Technologies and innovations were identified following a a broad exploration and review of primary, secondary and tertiary sources. We also delved into the number of patents registered and funding awarded. In addition to novelty and potential impact, technologies and innovations were selected based on adaptability, affordability and scalability. However, many technologies are at the early stages of research and development and their impact is unpredictable and cannot be guaranteed.

Structure of this report

- **Chapter 2** outlines the magnitude of the global energy challenge and identifies the opportunities to address the challenge.
- **Chapters 3-5** offer insights on selected emerging technologies and innovations in the rapidly growing field of renewable energy, with a focus on solar technologies.
- **Chapter 6** explores the potential impact of these novel and emerging technologies and innovations for children and the humanitarian and international development sector.

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2. Our energy challenge

The world is facing an energy trilemma.

1. Energy is critical for human development but 1 in 10 people in the world are without electricity.[7]
2. Energy consumption, of mainly fossil fuel, is driving environmental and climate crises globally. Global CO_2 emissions from fossil fuels hit record high in 2022.[8]
3. The demand for energy is increasing. Global energy use is predicted to increase nearly 50 per cent compared with 2020, mostly due to economic growth and population in non-OECD countries[9]

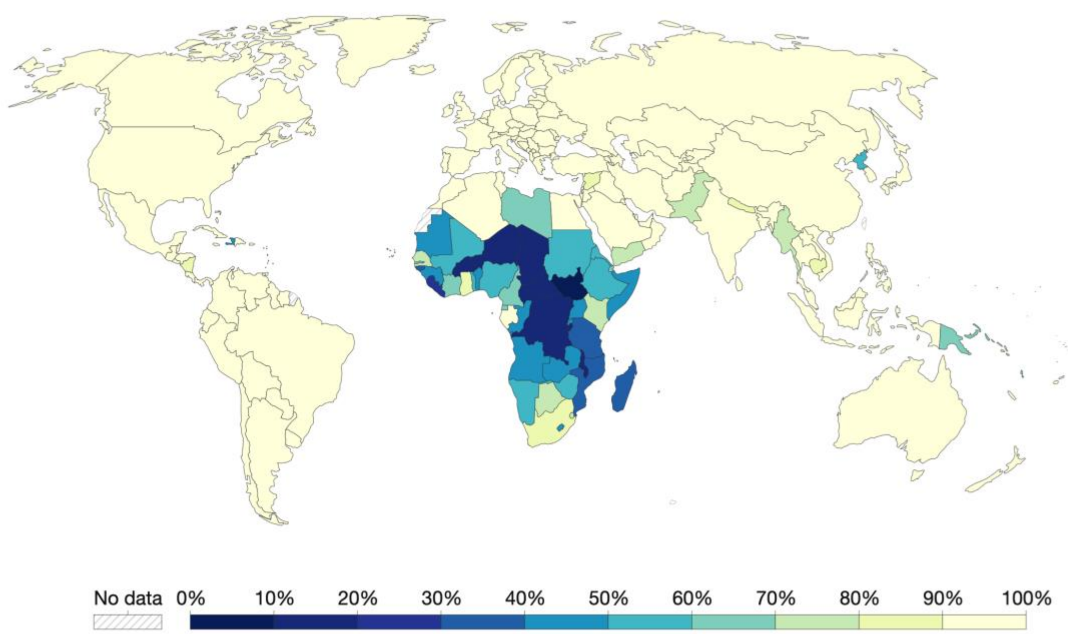
Below are ten inconvenient facts that illustrate the magnitude of the challenge posed by the current energy system and the impact of energy poverty.

1. 733 million people are without electricity in 2020 (Figure 3), nearly 80 per cent of whom live in Africa and especially in rural areas (Figure 4).[10]
2. 2.4 billion people use polluting cooking systems, 1 in 3 people in the world.[11] An estimated 600,000 children under age 5 die each year from respiratory infections related to indoor and outdoor air pollution and second-hand smoke resulting from unsustainable energy practices.[12]
3. 1 in 10 health facilities in South Asia and sub-Saharan African countries have no access to electricity.[13]
4. 1 in 4 children[14] or around 186 million children[15], attend primary schools without any electricity in mainly Sub- Saharan Africa, South Asia and Latin

America. Children living in electrified households spend 274 more days at school than those living in households without electricity.[16]

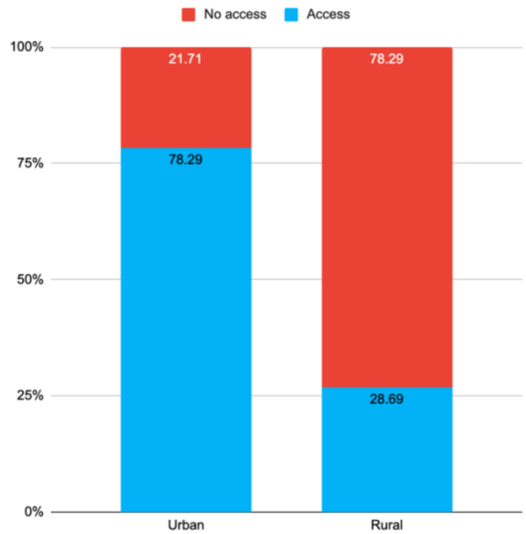
5. 8 million people died from fossil fuel pollution in 2018.[17]
6. Nearly a million stillbirths a year can be attributed to fossil fuel pollution.[18] UNICEF describes stillbirths as a neglected tragedy in a 2020 report.[19]
7. 82 per cent of global energy comes from fossil fuels in 2021.[20]
8. 75 per cent of global greenhouse gas and 90 per cent of carbon dioxide (CO_2) emissions come from fossil fuels.[21]
9. Only 13.5 per cent of global energy comes from renewables and 25 per cent of global electricity comes from renewables in 2021.[22]
10. International public finance flows to low-income countries to support clean energy was $10.9 billion in 2019, a drop of nearly 24 per cent from 2018.[23]

Figure 3: Access to electricity worldwide, 2020



Source: Electricity Access, 2020. Ritchie, H., M. Roser and P. Rosado, 'Energy', 2022, <https://ourworldindata.org/energy>. Data source: World Development Indicators - World Bank (2022.05.26)

Figure 4: Electricity access in Sub-Sahara Africa in 2020



Source: World Bank, World Development Indicators (2022.05.26)

Figure 4 shows that in 2020, 28.69 per cent of the rural population has access electricity in Sub-Sahara Africa, whereas 78.29 per cent of the urban population has access to electricity.[24] Without grid access, many communities rely on expensive and polluting energy sources such as kerosene, candles, dry cell batteries and diesel generators.

From challenge to opportunity

Our challenge is to provide accessible, affordable, reliable and sustainable energy, particularly electricity to all and reduce greenhouse gas emissions and reliance on fossil fuel.[25] *The UNICEF Sustainability and Climate Change Action Plan 2023-2030* stresses that the only long-term solution is to drastically reduce emissions while also ensuring that environmental sustainability translates to economic opportunity.[26]

Times of crisis put the spotlight on alternatives, possibilities and opportunities. The current energy security concerns and the environmental and climate crises is driving great interest in renewable energy. *The Global Roadmap for Accelerated SDG 7 Action* calls for action in five key areas: closing the energy access gap; rapidly transitioning to decarbonized energy systems; mobilizing adequate and predictable finance; leaving no one behind on the path to a net-zero future; and harnessing innovation, technology and data.[27]

Reliable and affordable energy will help improve the accessibility and quality of services, such as education, health, digital connectivity, and water, sanitation and hygiene (WASH) that children rely on for their survival, development and wellbeing. This is especially the case for children who are displaced by conflict or environmental and climate disasters. Without access to energy, they cannot study at night and they are unable to move around safely after dark, especially girls and women.

What we want to know

- What kind of technological innovations can advance energy equity, particularly for communities in low-resource rural/remote settings - places that are often hard to reach and where building and maintaining energy infrastructure is costly?
- How might we accelerate SDG 7 and decelerate the climate and environmental crises through harnessing novel and emerging technologies in the renewable energy domain?
- What is the potential impact of novel and emerging renewable energy innovations for children and the humanitarian and development sector?

03

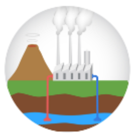
3. Opportunity: renewable energy

Renewable energy futures

Renewable energy is produced by using natural resources that do not run out. The most common sources of renewable energy are solar, wind, hydro bioenergy and geothermal. Table 1 is a summary of these six renewable energy sources.[28]

Table 1: Renewable energy sources

Renewable energy	Description
 Solar energy	• Solar energy is the most abundant of all renewable energy resources. • It is possible for every country to have solar as part of its renewable energy mix. • The cost of manufacturing solar panels has reduced dramatically in the last decade. • Solar is affordable for most consumers and often the cheapest form of electricity. • Advances in solar technologies have enabled the application to a range of climate resilient innovations.
 Wind energy	• Wind energy harnesses the kinetic energy of moving air by using large onshore or offshore wind turbines. • Most regions of the world have can generate wind energy. • Technically, wind energy is a form of solar energy because “wind” is caused by the differences in temperature in the atmosphere combined with the rotation of Earth and the geography of the planet. • Initial investment is relatively costly.

 Hydropower	• Hydropower is currently the largest source of renewable energy in the electricity sector. • Hydropower reservoirs can also provide drinking water, water for irrigation, flood and drought control and navigation services. • Relies on stable rainfall patterns, impacted by droughts or changes to rainfall patterns. • Costly to build the infrastructure for hydropower.
 Geothermal energy	• Geothermal energy is heat that is trapped beneath the earth's crust from the formation of the Earth (e.g. volcanic eruptions and geysers). • This heat can be captured and used to produce geothermal energy by using steam that comes from the heated water pumping below the surface, which then rises to the top and can be used to operate a turbine. • Not suitable for locations that are vulnerable to earthquakes. • Costly to build the infrastructure for geothermal energy.
 Bioenergy	• Bioenergy (biomass) is produced from a variety of organic materials, such as wood, charcoal, dung and other manures for heat and power production, and agricultural crops for liquid biofuels. • Most biomass is often used in rural areas for cooking, lighting and space heating, generally by low-resource communities.
 Ocean energy	• Ocean energy derives from technologies that use waves or currents to produce electricity or heat. • Wave energy is predictable. • Ocean energy systems are at an early stage of development with prototype wave and tidal current devices being explored.

Renewable energy can be used for electricity generation, space and water heating and cooling and transportation. Some types of renewable energy, like wind and solar power, come from sources that are not depleted when used. Others, like biomass, come from sources that can be replenished.

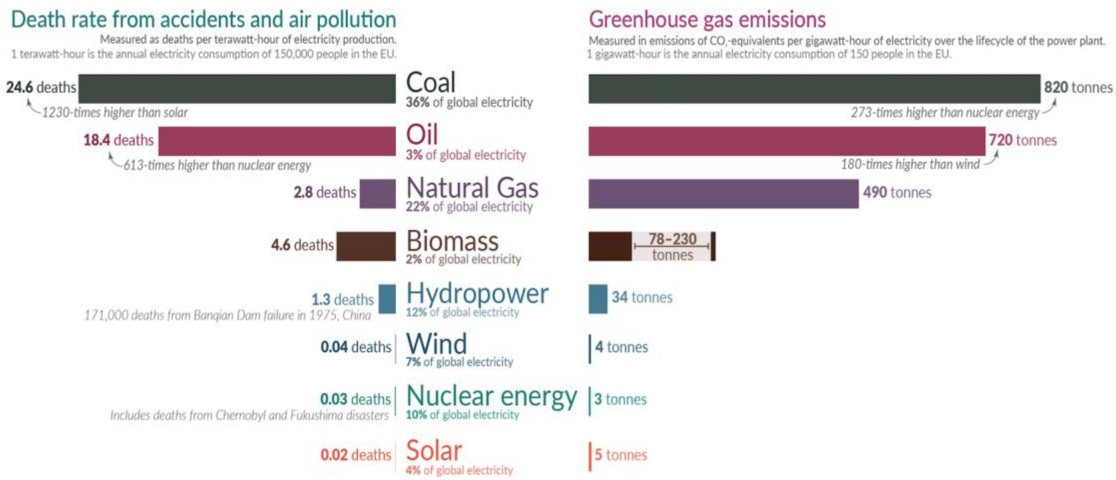
Renewable energy / carbon-free

The terms "renewable energy" and "carbon-free energy" need to be clarified. Not all renewable energy is carbon-free and not all carbon-free energy is renewable.

Bioenergy is renewable and not carbon-free. Plants absorb CO_2, while burning plants releases CO_2. The total CO_2 emission depends on how the bioenergy is produced. Nuclear energy is carbon-free but not renewable. A nuclear power plant does not emit any CO_2 or any other greenhouse gases. But nuclear reactors use uranium - a finite resource.

Generating renewable energy produces far less CO_2 and other harmful greenhouse gases and pollutants than non-renewable energy sources such as fossil fuels like coal, gas and oil. Most types of renewable energy produce no CO_2 once they are running. Figure 5 shows the greenhouse gas emission and air pollution from different sources of energy.

Figure 5: The safest and cleanest sources of energy

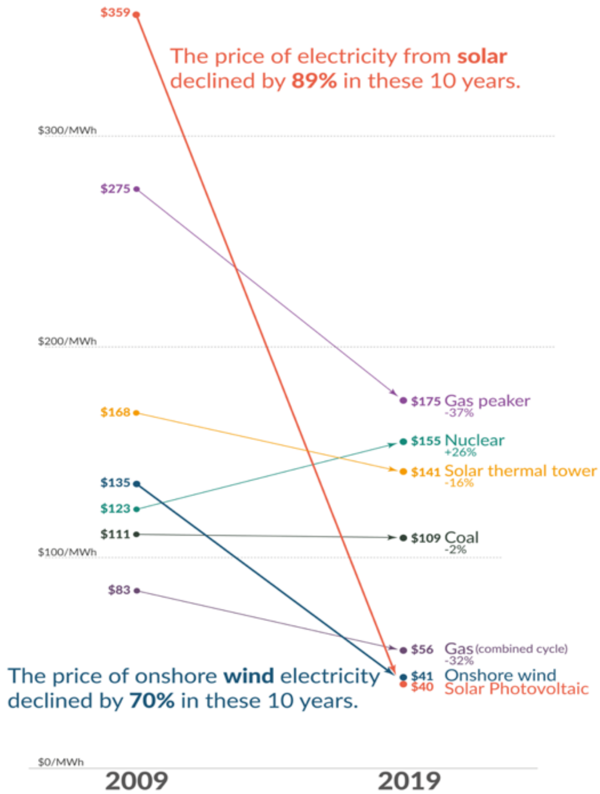


Source: Our World in Data, What are the safest and cleanest sources of energy? <https://ourworldindata.org/safest-sources-of-energy>, Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

The International Energy Agency anticipates solar PV and wind will account for nearly 95 per cent of global renewable capacity additions in 2027, while technology challenges and limited policy support have slowed expansion of hydropower, bioenergy, geothermal and ocean technologies.[29] Stanford University researchers collected 70 peer-reviewed publications from 25 research groups to analyze the technical feasibility of energy transition in a range of different scenarios and geographies, including small island states, major powers and countries in sub-Saharan Africa.[30] They concluded that energy for electricity, transport, and building heating or cooling can be supplied reliably with near 100 per cent renewable energy at different locations worldwide.[31] They also argued that for countries that are responsible for 99.7 per cent of global CO_2 emissions, they need to switch to 80 per cent renewable wind, water and solar power (optimized energy mix) by 2030 and 100 per cent renewables by 2050.[32]

Renewable energy is cheaper than fossil fuel

Figure 6: The decrease in price of electricity from renewables compared with fossil fuel, 2009-2019



Source: Our World in Data, The price of electricity from new power plants, Ver 13. Licensed under CC-BY by Max Roser.

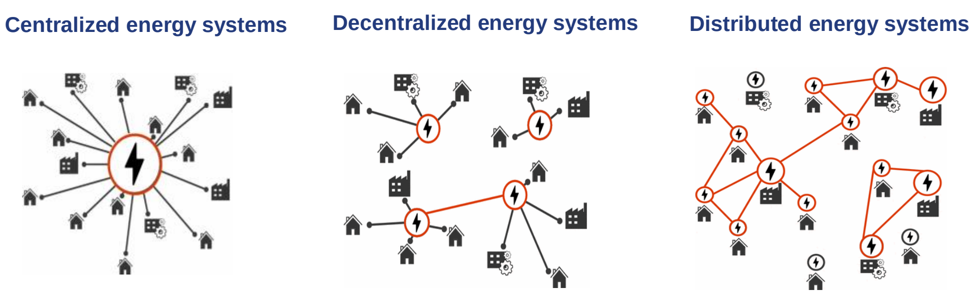
Energy produced from renewable sources are now cheaper than fossil fuel in most countries. Figure 6 compares the price of electricity, expressed in levelized costs of energy (LCOE), of different types of power source.[33] The most significant decline is the price of electricity from solar. Between 2010 and 2020, solar module prices fell by up to 93 per cent, as the cumulative installed capacity of solar photovoltaic (PV) grew from 40 gigawatts (GW) to 710GW.[34] This dramatic drop makes electricity generated from solar PV one of the most affordable forms of electricity, along with on-site wind power. But the gains are unevenly distributed. Without substantial investment in the renewable energy in middle and low-income countries, their people will continue to face the problem of affordability.

Distributed renewable energy

Distributed renewable energy, including off-grid and microgrid systems, are emerging as alternatives to large-scale energy infrastructure to facilitate energy access and resilience in a flexible and adaptable way, especially for communities in Sub-Saharan Africa and South Asia, who experience some of the world's biggest gaps in energy access. Not only can distributed renewable energy systems help to meet higher global energy demand, but they also help to reduce emission.[35]

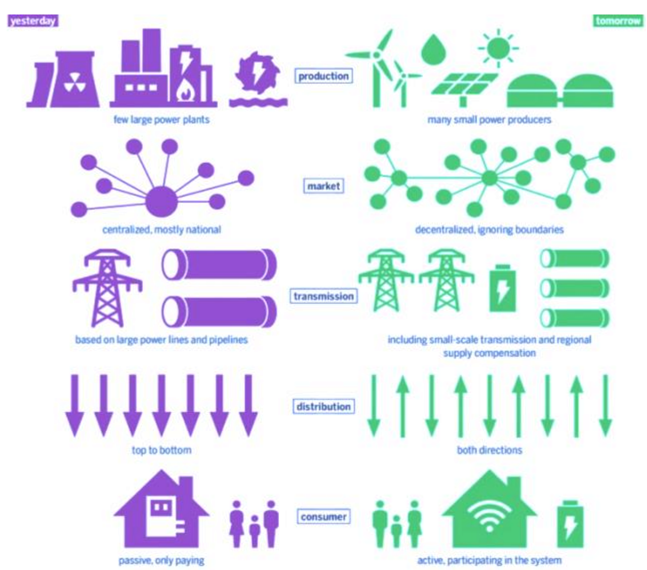
Distributed energy resource (DER) is any asset used for generating, storing, or distributing power that exist outside the central utilities-run power grid.[36] These can include assets like photovoltaic cells for solar energy, wind turbines, smart meters, and local battery systems. DER assets usually have a capacity less than 10 megawatts (MW). These renewable energy units or systems are usually located near the point of use, often at houses or businesses, and exist “behind-the meter,” meaning they are on the consumer-side of power grid metering systems where consumers are the producers - often called 'prosumers’.[37] DER differs from the traditional energy utilities such as the remotely located central power plants and high-voltage transmission lines necessary for large-scale electrical distribution. Figures 7 and 8 illustrate the difference between centralized and distributed energy systems.

Fig. 7: The difference between centralized, decentralized and distributed energy systems



Source: Vezzoli, C. et al. (2018). *Distributed/Decentralized Renewable Energy Systems*. *In: Designing Sustainable Energy for All. Green Energy and Technology*. Springer, Cham. https://doi.org/10.1007/978-3-319-70223-0_2, pp. 24.

Fig. 8: The structural changes anticipated in transitioning to distributed and decentralized renewable energy system.



Source: Emmerich, P., ‘How smart grid technologies are disrupting the energy sector’, Energy Transition <https://energytransition.org/2021/07/how-smart-grid-technologies-are-disrupting-the-energy-sector/>

A distributed and decentralized renewable energy system will require at least five fundamental changes:

1. Energy generation and production.
2. The energy market and business models as more and new service providers enter the system.
3. Transmission infrastructure.
4. Energy distribution and storage technologies to manage irregular loads and demands.
5. Devices for consumers to be energy producers and active participants of the system.
6. Distributed energy networks, when combined with digital technology, become smart grids that enable real-time monitoring of transmission and two-way communication between the utility and its customers.

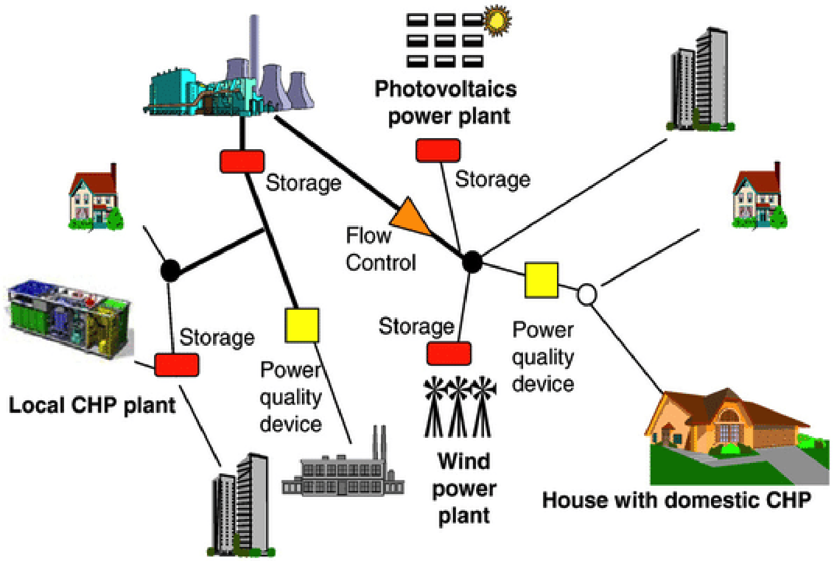
Microgrids

In low-resource and remote settings, microgrids are playing an important role in electrification. Microgrids are flexible, cost-effective and modular architectures for deploying distributed energy resources that can meet the needs of different communities from Myanmar to Ethiopia, for whole communities or single sites like hospitals or schools. The World Bank is leveraging $1.2 billion in co-financing to accelerate the deployment mini grids at unprecedented scale.[38] In MICs and LICs, microgrids open opportunities for energy entrepreneurship, particularly, where most communities currently rely on diesel, which releases large amounts of carbon emissions.

Distributed renewable energy challenges

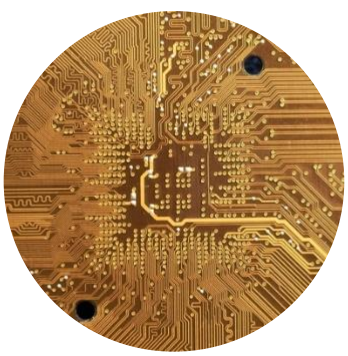
The high penetration of distributed renewable energy resources in the energy market is not a simple 'plug and play' operation. The transition requires collective problem solving across the value chain to come up with support, technical, market, and workforce solutions, particularly technologies in intelligence and interoperability to improve energy management in distributed energy systems. Power systems with high levels of distributed energy resources are prone to congestion and instability because demand and supply tend to be unpredictable. As Figure 9 shows, a distributed energy system is highly complex and needs to be able to effectively stabilize and optimize energy consumption optimization in real time.

Figure 9: An example of distributed energy generation with integrated network management



Source: Moreno-Muñoz, A., et al., 'Grid interconnection of renewable energy sources: Spanish legislation', *Energy for Sustainable Development*, vol. 14, no. 2, 2010, p.105, doi: 10.1016/j.esd.2010.03.003.

Renewable energy and quantum computing



One of the biggest barriers to scaling up the transition to renewable energy is system stability and optimizing an energy system with highly distributed and varied renewables that are often influenced by weather conditions. Some energy experts believe that challenges around energy demand and response modelling and analysis are too difficult to solve with traditional computers running programmes based on binary codes.[39]

Quantum computing relies on the laws of quantum mechanics to perform types of information processing that are not possible on traditional computers. It provides a new way to solve complex optimization problems from power generation, transmission, distribution to demand management in distributed renewable energy systems.[40] A few areas where quantum computing is likely to contribute to renewable energy problems include, simulation, scheduling and dispatch, optimization and cybersecurity.[41]

Predictive analytics for optimizing energy grids

Load scheduling problems present opportunities to fully leverage quantum computing's strength. Quantum computing's strength in handling binary variables offers a great tool to derive optimal on and off decisions to manage schedulable loads (e.g., electric water heaters, refrigeration system, air conditioning units) for balancing the intermittency of renewable resources.[42]

The application of quantum machine learning for predictive analytics could provide real-time and highly accurate predictive analytics for energy optimization. By analyzing large amounts of data from sensors, weather forecasting, homes, businesses and so forth, quantum computing can make highly accurate predictions of energy demand and supply, which will improve the stability and efficiency of the grid.

> Quantum computing is an emerging technology and the deployment of large-scale, fault-tolerant quantum computers is far into the future. But companies like D-Wave, Google, Honeywell, IBM, and IonQ are investing in this space. European utility E.ON is experimenting with IBM's quantum computing capabilities to optimize decentralized power generation.[43]

Energy storage and distribution

One of the most pressing issues in renewable energy is storage and distribution. Quantum computing can simulate the behavior of materials at the atomic and molecular level, giving researchers the ability to design more efficient and cost-effective energy storage solutions.[44] For instance, quantum computing can optimize the design of batteries, resulting in longer-lasting, higher energy density devices. It can also be used to improve the efficiency of solar cells, thereby reducing the cost of solar energy. Table 2 outlines some of the potential uses of quantum computing for energy and climate change.

Table 2: Potential benefits of quantum computing for energy and climate challenges

Category	Challenge	Possible benefits
Climate modeling and weather forecasting	Meeting computational needs as the complexity and resolution of simulation and forecasting models grow.	Greater capability to solve fluid dynamics–based simulations could facilitate model improvements, allowing clearer understanding of likely future conditions and improving mitigation and adaptation planning.
Grid safety and resilience	Ensuring power generation facilities are robust and reliable in the future.	Enhanced weather and climate models could allow for safer siting of infrastructure, and quantum optimization can be applied to improve the design of new resources like wind farms.
Grid management	Scheduling and dispatching resources to match supply and demand, especially as the number and distribution of generators increase.	Quantum optimization could help create cost-effective management solutions and could lower consumer prices by improving operating conditions (e.g., by solving alternating current optimal power flow equations).
Quantum chemistry	Evaluating molecula scale properties and processes of a vast array of materials to foster technology innovation.	Quantum computing could accelerate discovery and development of new energy production (e.g., photovoltaic) and storage (e.g., battery) technologies, as well as improved strategies for climate change mitigation.

Source: Giani, A., and Z. Goff-Eldredge (2022), 'How quantum computing can tackle climate and energy challenges', *Eos*, vol. 103, 21 October 2022, doi: 10.1029/2022EO220500, <www.eos.org/features/how-quantum-computing-can-tackle-climate-and-energy-challenges>.

04

4. Opportunity: solar energy technologies

Energy created by the heat and light of the sun is called solar energy. Solar power is produced when energy from the sun is converted into electricity or used to heat air, water or other substances. Solar energy can be used to create solar fuels such as hydrogen. But solar energy is variable because solar irradiance varies significantly with geographic location and climate conditions.[45]

This section focuses on solar cell technologies and novel innovations enabled by emerging (third generation) solar cells. The capacity of solar energy technologies to add value to a range of sectors and to mitigate climate change surpasses other sources of renewable energy. For example:

- It is the cleanest, safest and cheapest source of electricity. (The cost of wind power is similar.)
- Solar technologies can be deployed to generate electricity, moderate sunlight for agriculture, and contribute towards zero-carbon built environments.
- Adaptability - solar energy systems can grow as demand and consumption increases, and investment becomes available. In terms of microgrids, new components could be added without requiring major system rework. An off-grid solar system can be fully assembled and tested prior to delivery to a remote location. This means the onsite deployment time can be kept to a minimum.

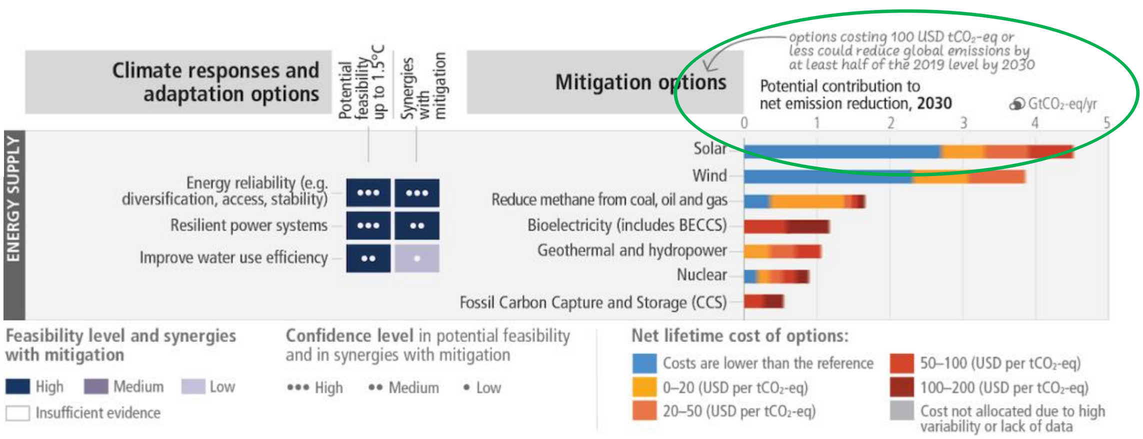
- Affordability - the establishment and maintenance costs are relatively low compared to other renewable energy sources.
- Durability – the product lifespan is around 30 years. The lifespan of a wind turbine is about 20 years.

The IPCC Sixth Assessment Synthesis Report 2022

The latest IPCC Synthesis Report, based on over 12,500 pages of research (400,000 publications on climate change since 2018), has modelled pathways and opportunities for scaling up climate action and the feasibility of climate responses and adaptation for the near term.[46]

Figure 10 is a snapshot of the potential impact and relative cost of transitioning the energy supply and deploying solar for emission reduction and adaptation by 2030. Costs are net lifetime discounted monetary costs of avoided greenhouse gas emissions calculated relative to a reference technology. Solar energy as a core component of an energy generation diversification strategy will help reduce climate-related risks, but the potentials and costs will vary by place, context and time and in the longer term compared to 2030.

Figure 10: The IPCC identifies solar energy as a highly feasible and impactful mitigation option.



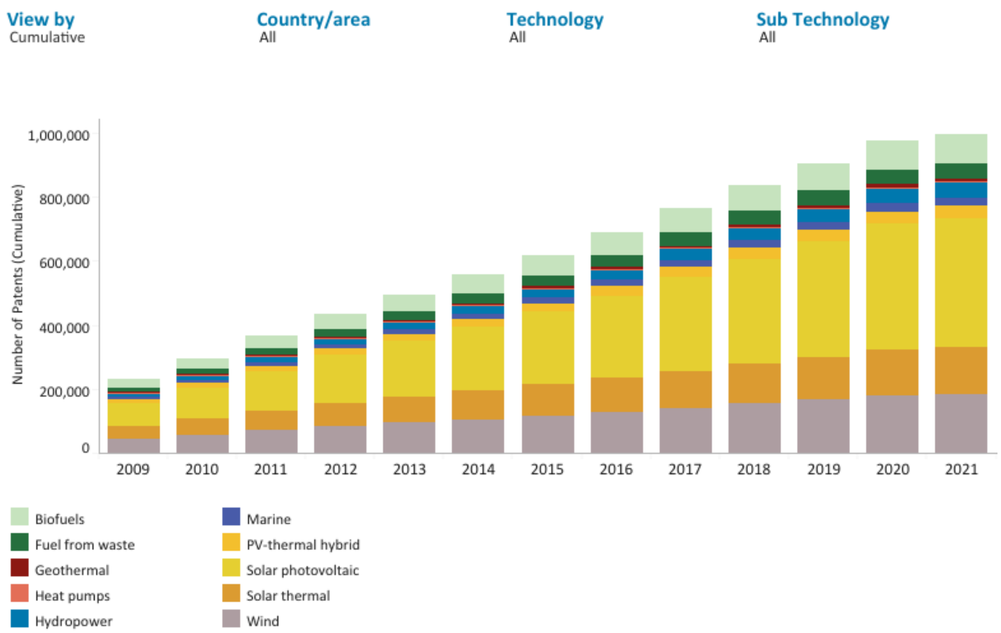
Source: IPCC Sixth Assessment Synthesis Report, SPM Figure 7, p.69

Solar technologies dominate innovations in the renewable energy sector.

Incentives and investments in research and development in solar energy have helped drive the rise of solar power and innovation in the sector. Patents are widely used indicators of how much innovation is happening, where and in which fields.

Figure 11 shows the impressive growth rate in patent applications on solar energy – solar PV, solar thermal and PV-thermal hybrid. In particular, the number of patent applications filed for solar photovoltaic have accelerated. It should be noted that patents are long-term investments. The innovations may take many years and through stages of scientific and financial feasibility and viability before they may come to market.

Figure 11: Renewable Energy Patents November 2022



Source: IRENA INSPIRE (www.irena.org/Inspire) based on EPO PATSTAT 2021 Autumn edition, and on the Climate Change Mitigation Technologies (Y02) classification by EPO. ©IRENA

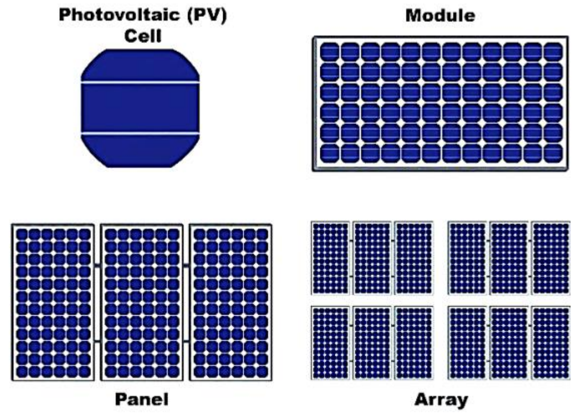
Note: This not exhaustive information on patents filed for renewable energy worldwide and does not represent all inventive activity worldwide. Some inventors may choose to file individual patent applications.

Two main types of solar energy

Solar photovoltaic

Solar photovoltaic converts sunlight into electricity using a technology known as a semiconductor cell, commonly a type of solar PV cell. Solar cells are then connected and encased in glass and an aluminium frame to form power-generating units known as modules or panels (Figure 12). One or more panels can be installed to power a single light, cover the roof for residential use, or be assembled into a large-scale solar farm generating hundreds of megawatts of electricity.

Figure 12: From a solar cell to module, panel to array.



Source: University of Central Florida FSEC®

Solar thermal

Solar thermal technologies convert sunlight to heat space or water (such as a solar hot water system), help regulate internal temperature of a dwelling, and create steam to drive an electricity generator. For example, solar thermal air conditioners use solar collectors that heat a liquid that passes through the system and then evaporates and condenses, creating cool air.

Concentrated solar thermal (CST) systems use mirrors to concentrate a large area of sunlight into a targeted location to produce intense heat. This heat is captured using a fluid, such as molten sodium, which is then used to heat water to create steam to power a turbine and produce electricity. CST is currently more expensive than other renewables, such as solar PV and wind for electricity generation. However, this could change soon as CST technology improves and the capacity of CST to store for long periods and dispatch energy with little energy loss when needed become increasingly valuable.

Solar thermal for heating water

Solar thermal air-conditioning

Concentrated solar thermal

Solar cell technologies

Solar cell technologies are the critical enablers for solar innovations. Advances in solar cell technologies expand opportunities for novel applications of solar energy, with spillover benefit for many related technologies.

What is a solar cell?

A solar cell (or photovoltaic or PV cell) is a device that converts light energy into electricity through the photovoltaic effect. The photovoltaic effect is the effect of light energy being converted to electric energy when exposed to light in certain semiconductor materials.

How do solar cells work?

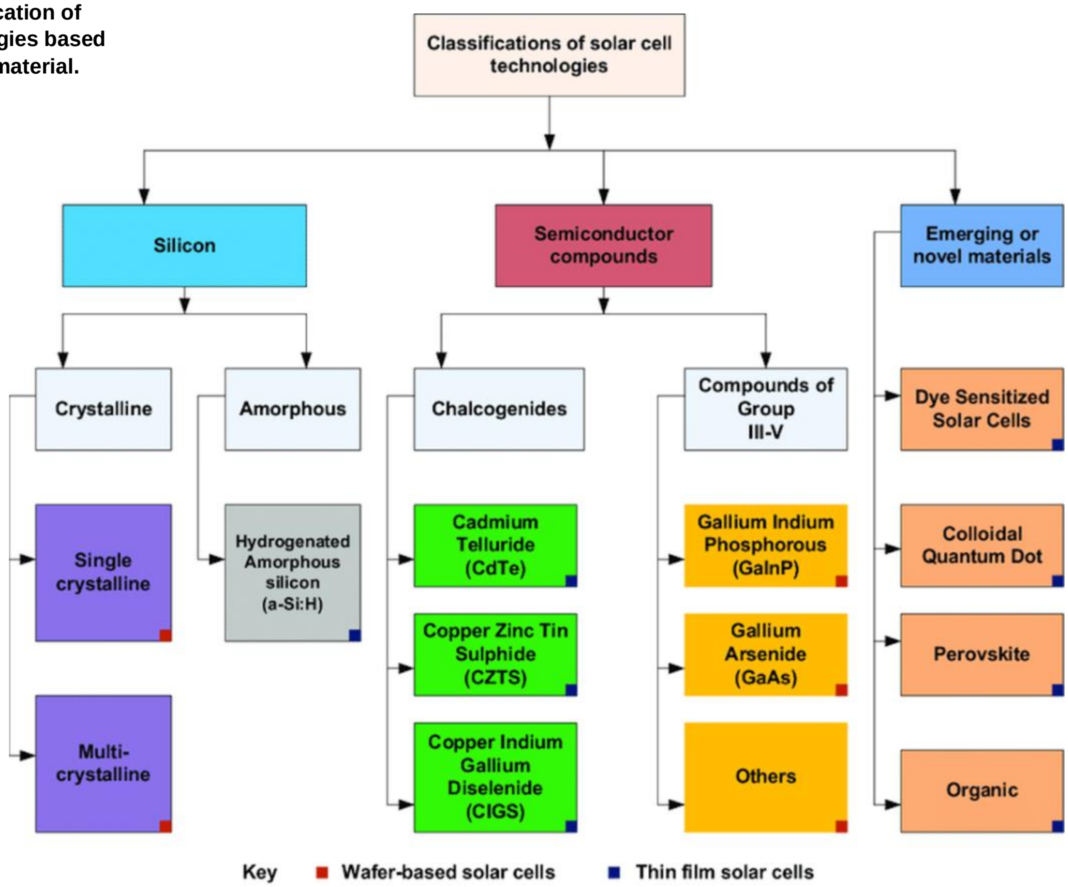
The key component of a solar cell is the semiconductor**.** To transform light energy into electrical energy, photovoltaic solar cells rely on semiconductors - substances that lie in the range between metallic conductors like copper and electrical insulators like glass. Semiconductors convert light energy to electrical energy due to the structure of their electron energy levels. Sunlight energizes the semiconductor material's electrons and generates an electric current. A solar cell's ability to convert light into electricity is known as the power conversion efficiency (PCE).

Types of solar PV cells

Different types of semiconductor materials are used to make different types of photovoltaic cells, with varying electrical properties such current, voltage, and resistance.

There are currently around 25 types of solar cells based on inorganic and organic semi-conductor materials and hybrids. Solar cells are classified according to the material used (Figure 13) and grouped into three generations. The performance of photovoltaic cell (conversion efficiency) is the percentage of the solar energy shining on a PV device that is converted into usable electricity. Figure 14 shows the conversion rates (%) of solar cells and the institutions leading the research in the field.

Figure 13: Classification of solar cell technologies based on primary active material.



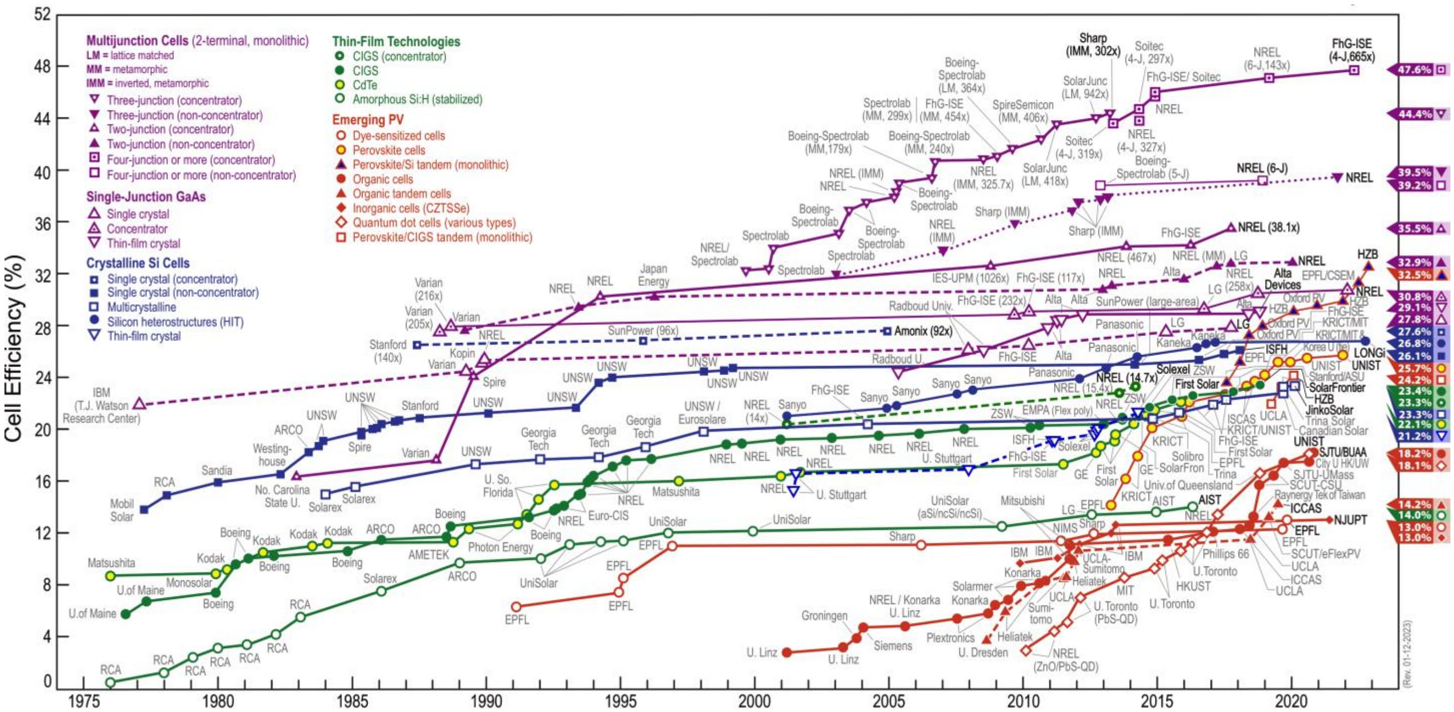
Source: bn-Mohammed, T., et al., 'Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technology', *Renewable and Sustainable Energy Reviews*, vol.80, 2017, pp. 1321-1344, doi: /10.1016/j.rser.2017.05.095.

- **First generation solar cells**. The first generation solar photovoltaics are well-matured in terms of their technology and fabrication process. They are based on crystalline silicon (c-Si), a well-studied inorganic semiconductor, and are the oldest commercially available photovoltaic technologies. The silicon solar cells require a purity of up to 99.99 per cent. The production process is complex, with high energy consumption and pollution. Most solar cells on the market are based 'first generation' solar cell technology on silicon wafers.
- **Second generation solar cells**. The second generation solar cells are based on thin-film technology where the active layer of PV material is much thinner than with first generation crystalline silicon (c-Si) solar cells.[47] Thin film solar cells are based on inorganic semiconductors such as copper indium

gallium selenide (CIGS), cadmium telluride (CdTe), gallium arsenide (GaAs) and amorphous silicon (a-Si:H).[48] Thin active layers reduce manufacturing and module cost and open the potential for flexible and semi-transparent solar cells.[49] The manufacturing of these PVs produces highly toxic by-products.

- **Third generation solar cells – emerging cell technologies**. Third generation solar cells are hybrids of organic and inorganic materials that can be made in a laboratory and at scale.[50] These solar cells are remarkable because of their ability to make electricity can be 'tuned' by controlling the kinds of molecules that are produced in the manufacturing process.[51] This tuning results in materials with the ideal bandgap (or energy gap), which is the amount of energy needed to push an electron to a higher energy level so it can carry an electrical charge across a circuit.[52]

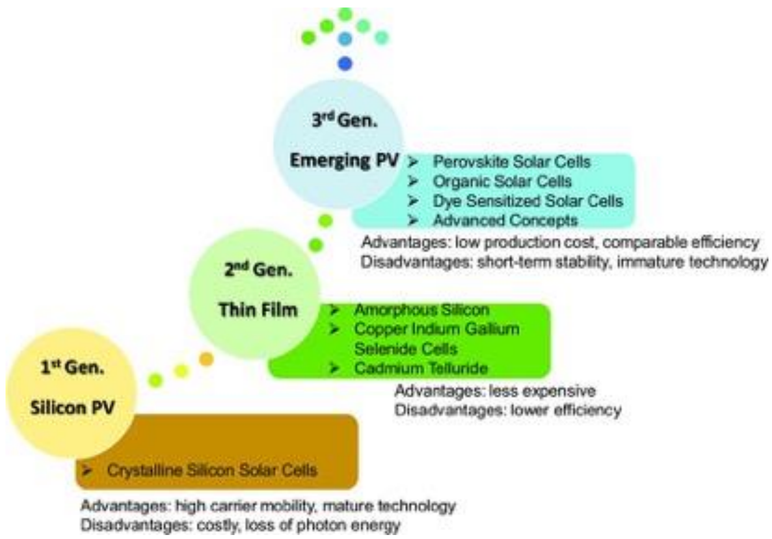
Figure 14: Solar cell efficiencies – conversion of solar energy to electricity, 1975-2023



Source: National Renewable Energy Laboratory, Best research-cell efficiency chart, 2020 <nrel.gov/pv/cell-efficiency.html>.

To become commercially viable, the development of third generation photovoltaic technology will need to overcome the problem of short-term stability and reduce the cost of constituent materials such as the top cover sheet and other encapsulants required to maintain a 30-year operating life of solar cells.[53] Nevertheless, research to date suggests that the evolution of new materials technology will enable third generation thin-film PV to improve towards the highest possible efficiency. Figure 15 illustrates the level of maturity of each generation of solar cell.

Figure 15: Maturity of each generation of solar cell technologies



Source: Pham, H. D., et al., 'Development of Dopant-Free Organic Hole Transporting Materials for Perovskite Solar Cells', Advanced Energy Materials, 1903326, 2020, doi: 10.1002/aenm.201903326.

The next section will explore some novel and emerging solar innovations that have been made possible due to development in third generation solar cells.

Emerging PV technology - Perovskite

Silicon solar cells currently dominate the market. But they take a lot of energy to produce and are rigid and tend to fragile. Perovskite PV matches the performance of silicon cells and can be printed out using special inks and wrapped flexibly around uneven surfaces. Perovskite PVs are predicted to overtake silicon PV in the solar market in the coming decade.

The term perovskite refers to a group of compounds and describes a material with a specific crystal structure.[54] These crystals are naturally occurring in the form of calcium titanate and when combined with certain organic and inorganic materials, you have a perovskite semiconductor.[55] Perovskite solar cells first appeared in research labs in 2012.

Potential benefits

a) Perovskite is much less expensive to produce than silicon. While silicon must be heated to extremely high temperatures to produce material with the right purity and crystal structure to make electricity, perovskites can be created by mixing chemicals in solution and coating a surface with that solution.[56]
b) In comparison to other emergent photovoltaic technology and traditional thin-film photovoltaics, the power conversion efficiencies of the perovskite-based devices have improved most dramatically over recent years.[57]
c) Perovskite solar cell conversion energy loss is usually 30 per cent or less compared to energy loss in the conversion process from light to electricity, which can be as high as 50 per cent.[58]
d) Perovskites can be flexible, lightweight, and even semi-transparent. It absorbs visible light very efficiently. This means that devices can be achieved high efficiency with a very thin perovskite layer.
e) They can be made with methods like slot-die coating and ink jet printing. This feature opens the way for potential solar energy solution, such as factories printing solar modules at an extraordinary rate on massive rolls and solar paint or spray for solar cells.[59]

f) Perovskites solar cells can be stacked on top of a silicon solar cell to create multiple solar devices to increase energy conversion efficiency that is significantly higher than either C-Si or perovskite solar cells individually.[60]

g) Perovskites solar cells could be easily deposited onto most surfaces, including flexible and textured ones.[61]

Constraints

a) *Stability.* The biggest issues in the field of perovskites are long-term instability, particularly involving external factors, such as water, light, and oxygen and intrinsic instability due to heating.[62]

b) *Durability.* Perovskite materials have great potential as a lightweight and low-cost option for solar panels but have not been seen as durable enough for widespread use in large-scale solar-power installations. Improving perovskite durability is a challenge. They are susceptible to degradation through extrinsic factors, such as moisture, oxygen, heat and light, as well as intrinsic processes, which limits its commercial application at the moment.[63] While silicon solar panels retain up to 90 per cent of their power output after 25 years, perovskites degrade much faster.[64]

c) *Toxicity.* Many efficient perovskites are based on metal halides (lead) and moving beyond this has proved challenging. Lead-based perovskite-based solar cells are excellent for strong absorption in the visible regime, and for long, charge-carrier diffusion lengths (a tuneable band gap).[65] Perovskites are easy to manufacture but there are concerns about exposure to toxic lead compounds through leaching of the perovskite into the environment.[66]

Emerging PV technology - Organic PV

Organic PVs (OPVs) are solar cells that use organic polymers and nanocomposites as active layer for light absorption and charge transport.[67] OPVs are sometimes referred to as “plastic solar cells” or “polymer solar cells".

Potential benefits

a) Compared to silicon PVs, production methods for organic PVs are low-cost and environmentally friendly, and result in a lightweight flexible substrate that can be mass produced at scale using roll-to-roll processing.[68] Organic PVs could reduce the cost of solar panels because purifying sand into high-grade silicon is a costly process.
b) Whilst several other PV technologies have higher efficiencies, OPVs remain significant due to the tunable electronic properties, low material toxicity, ease of processing, compatibility with thin cells and low environmental impact.
c) OPVs are made with compounds that are typically dissolved in ink and printed onto thin plastics, which means OPVs can be flexible and incorporated into more places or structures than crystalline PV.[69]
d) OPVs can be semi-transparent and use for windows (solar glass) or screens for mobile devices.
e) They are ultra-flexible and ultra-lightweight and can bend or curve around structures. They can also be integrated into clothing.

Constraints

a) The efficiency of organic solar cells, topping at around 14 per cent, lags behind silicon solar cells conversion rate of between 15-25 per cent.[70]
b) OPV commercialization is constrained by challenges of long-term stability issues due to photochemical degradation (sunlight).[71]
c) Organic cells are also vulnerable to moisture and oxygen. This problem can be fixed by the process of incapsulating the cell, but this adds to the production cost and unit weight and reduces efficiency even further.[72]

Emerging PV technology - Quantum dot

Quantum dots are nanoparticles made from semiconducting material that are about 1/10,000 the size of a human hair.[73] The idea of using quantum dots to generate high energy efficiency was first noted in 1989. The application of quantum dot to solar cell technology is a promising breakthrough because it can potentially replace bulky materials that are currently used to produce solar PVs.

Potential benefits

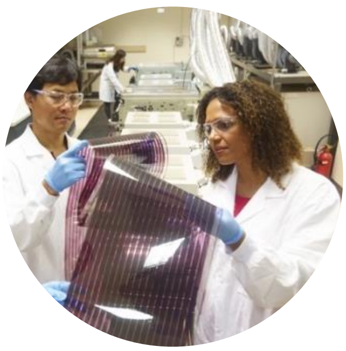
a) Theoretically, quantum dot PVs would be cheaper to manufacture because they are made through chemical reaction.
b) Quantum dot can be used to develop quantum dot 'only' solar cells or be used in inorganic or organic hybrids to enhance performance of PV cells, especially increase the efficiency and scalability of perovskite PV.[74]
c) Quantum dot sensitized solar cells are flexible and can be printed at a large scale in a cost-effective way, such as inkjet printing and spin coating processes. With further development, they may take the form of transparent skins for wearable electronic devices and on top of planes, cars, and houses to generate electricity.
d) Quantum dot solar cells can produce energy with solar and UV light.
e) The energy range of quantum dot solar cells are tunable by changing the dot size.

Constraints

a) In the lab, quantum dot solar cells can potentially increase the attainable thermodynamic conversion efficiency of solar conversion up to 66 per cent.[75] In real world use, they lag behind the efficiency of standard solar cells.
b) Cadmium selenide-based quantum dot solar cells are toxic and require stable polymer shells. But the shells make the size of the particles hard to control.
c) Quantum dot materials often oxidize and lose performance when exposed to ambient air, and are also sensitive to raised temperatures, moisture (humidity) and other conditions they would be sure to face installed in an outdoor setting.[76]

Novel solar innovations enabled by Third Generation PV cells

The unique properties of emerging PV cells have multiple flow on benefits to related technologies. They have enabled improvements to existing technologies and development of novel solar innovations, thereby broadening the range of potential application of PV technologies. The following are some promising innovations under development.



Solar film

Solar film is electronic solar inks printed onto sub-millimetre thin plastic sheets. If the solar cells are printed on polyethylene terephthalate (PET), the material can be recycled – an advantage over traditional silicon panels. The solar film is lightweight, highly flexible, semi-transparent, and can come in a range of colours. This solar film is roll-to-roll processed using established printing and coating techniques that are directly translatable to industry.[77] Printed solar is cheap to manufacture. It could produce kilometres of material a day using commercial equipment. The energy payback time is around one third that of silicon solar panels.[78]

Potential applications

a) Solar film has a range of applications when power is needed quickly and temporarily.
b) Printed solar cells are about 300 times lighter than traditional silicon cells. This addresses the challenge that many roofs in low-income countries cannot support the weight of the number of traditional silicon solar panels required to meet energy demands.
c) Retractable recharging systems for electric vehicles, caravans/camping
d) Suitable for floating solar farms which is attracting interest in the Asia Pacific.
e) Floating covers for dams and pools.
f) Integration into building products e.g., roofing materials and smart blinds for residential and high-rise buildings.
g) Integration into portable consumer products, e.g., in a laptop bag to charge a computer on the go.

Solar paint

Solar paint is a liquid with PV properties that allows it to absorb sunlight and convert it into electricity. Although solar paint is not yet commercially available, the simplicity of the fuel production process, its wide application and affordability are major factors as to why this new form of solar paint could be a game change.[79]

There are 3 types of solar paint.

1. Quantum dot solar paint, which due to the small size of these tiny semiconductor nanocrystals makes it possible to capture nearly all incident visible sunlight with an extremely thin layer of dots.[80]
2. Hydrogen solar paint combines synthetic molybdenum sulphide - which absorbs moisture from humid air, and titanium dioxide, which absorbs sunlight absorbs moisture from the air.[81] The sunlight and warmth break the liquid down into oxygen and hydrogen, the latter is used to produce energy.[82]
3. Perovskite solar paint is spray-on solar cells. Adding a layer of transparent coating material on top of the perovskite solar paint can produces electrical conductivity 10 times greater than solar paint alone.[83]

Potential applications

a) The paint can be coated on almost any surface and existing structure – especially roofs and the exterior of residential buildings, making them energy-harvesting and fuel-producing surfaces.
b) Hydrogen solar paint is adaptable to a range of climates. Any place with water vapour in the air – even remotes areas far from water – can produce fuel and it does not require any external power source to function.
c) Roadways and parking lots.

Solar glass

Solar glass looks like conventional window glass but features photovoltaic glazing that encloses solar cells that convert sunlight into renewable energy. Over the past ten years, the number of PV patent filings, among which are solar glass, have risen by roughly 200 per cent in Europe. The efficiency of solar glasses depend on their opacity. The solar glass with higher opacity is more efficient, but being less transparent means, it lets in less sunlight.

The technical challenge in commercializing solar glass is balancing three key areas – making it highly transparent, highly efficient, and highly resistant to degradation.[84] Several companies are developing transparent solar glass and solar glass that can operate in as little as 10 per cent sunlight.[85]

Potential applications

a) Solar glass can be designed and integrated into a building and perform effectively in locations and conditions where traditional crystalline silicon panels cannot.
b) Solar glass can be integrated into skylights and other roofing systems.
c) Researchers are testing the use of solar glass to provide enough power to run heating or cooling for greenhouses, as well as desalination to provide water.[86] As solar glass could be tailored to suit the growing conditions for particular plants, this could turn deserts into productive agricultural land.[87]

Office of Innovation

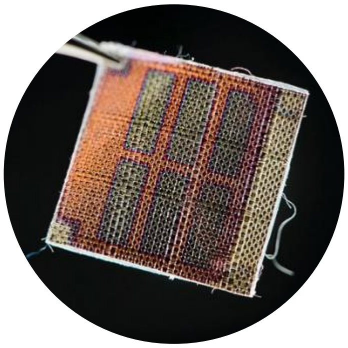
Agrivoltaic farming

Scientists and technologists in Kenya, South Korea, India, Australia and Canada have achieved promising results with deploying solar glass for farming.[88] The next generation agrivoltaic have a notable impact on creating microclimatic conditions with multiple synergistic benefits, including decrease water consumption by reducing the rate of evaporation from soil and transpiration from plants, protect crops and fruit trees from winter frost and extreme weather, improve food production, reduce PV panel heat stress, and help moderate ground temperatures.[89]

The latest solar glass technology allows 70 per cent of visible light to pass through, while block 90 per cent of solar UV and IR radiation and could be customized or 'tuned' to produce the perfect growing conditions for certain plants.[90] These unique features make solar glass suitable for parts of the world that are often too hot and dry for traditional greenhouse agriculture.

Another emerging innovation for agrivoltaics is transparent concentrator solar panels. According to Insolight, a Swiss startup founded by researchers from École polytechnique fédérale de Lausanne, the transparent panel has an efficiency rating of 30% and purportedly let through up to 78% of sunlight.[91] Interestingly, the cells only cover 0.5% of the panel surface and are covered with protective glass and optical lenses to concentrate and direct sunlight onto them at around 100 times the intensity of standard solar glass.[92] This could drastically reduce the cost of production and accelerate the demand for the innovation.

The results of these pilots provide a foundation for further explorations how integrating food and energy systems can address environmental and climate stress and improve food security.



Solar textile

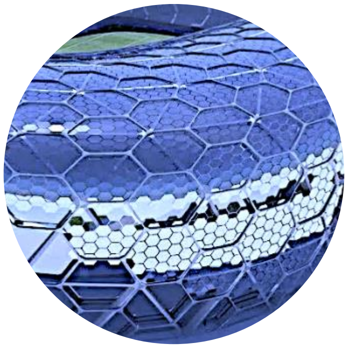
Solar textile is made by embedding miniaturised solar cells into yarn. The solar cells are made up of one layer of fabric and different polymers, including dye-sensitized PV cells.

An increased use in wearable, mobile, and electronic textile-sensing devices has led to a desire to keep these devices powered without the need for frequent recharging or bulky energy storage.[93]

The conductivity of the solar textile is determined by the underlying textiles.[94] Some fabrics absorb sunlight and keep it there as heat. Other fabrics dispensed the heat but conducts electrons. Other research is underway to make solar fabric that is one atom thick and 100 per cent recyclable.[95]

Potential applications

a) Solar filaments can be woven into the fabric for winter coat, gloves, or any other piece of clothing.
b) Solar textiles can used for awnings over buildings' windows and doors to capture and store energy for outdoor lighting.
c) Solar textiles can be used for shade sails that are often in shopping centre car parks or covering the local pool and sporting stadiums.
d) Solar fabric can be used to put together refugee camps. Solar tents can be erected in disaster zones and cheap, accessible power can be deployed rapidly to meet the needs of the most vulnerable.
e) Recent research has led to the development of fibre-based electronic, optoelectronic, energy harvesting, energy storage, and sensing devices.[96] Solar textile will accelerate innovation in wearable devices such as watches, glasses, bracelets and other compact solar products.



Solar skin

Solar skin is solar cells with polymer membrane that can generate power from direct and indirect sunlight and from vertical and horizontal surfaces. The polymer membrane protects the solar cell and is highly flame retardant.[97]

Potential applications

a) Solar skin that passed stringent fire and building safety regulations can be used to coat the outside of homes, building, infrastructure.
b) Solar skin provides affordable and reliable electricity in remote communities and in emergency and humanitarian situations.

Solar skin - haptic

Scientists from Glasgow University have developed a solar-powered synthetic skin with touch- and proximity-sensing capabilities but without using a touch sensor.[98] The solar cells are located on the graphene surface and work like body skin to generate power and provide tactile capabilities for touch and proximity sensing. There have been experimental applications of touch-sensitive electronic skin in prosthetics and robotics before, but this is the first energy-generating electronic skin capable of offering touch feedback without using dedicated touch sensors.[99]

Potential application

a) The solar-powered synthetic skin could be used in both robotics and prosthetics. Allowing prostheses to make highly improved pressure measurements would give amputees a much wider range of motion, including grasping and moving items that are currently too small to do with finesse, such as moving a computer mouse.[100]
b) Solar smart skin allows energy autonomy for wearable electronics used to monitor health.

05

5. Opportunity: renewable energy storage

As the global transition to renewable energy is gathering speed, there is an urgent need for flexible energy-storage technology to coordinate renewable energy sources for energy consumption.
Renewable sources of energy are plagued by fluctuations due to varying wind and solar intensity, resulting in a lack of stability if the energy supplied from such sources is used in ‘real time’. The problem is how to store the energy to make use of it in a controlled manner later as required.

Renewable energy storage technologies must:

- address fluctuation of distributed power sources,
- enhance the power flow, voltage control and self-recovery capabilities of the distribution network,[101]
- optimize resource allocation, and
- have large-capacity long-duration storage and fast response capabilities.

Energy storage technologies are classified according to the five storage principles: electrical, mechanical, electromechanical, chemical, and thermal. Table 2 provides an overview of the five types of energy storage, advantages and disadvantages and examples of technologies under each classification.[102]

Table 3: Overview of selected energy storage technologies

Storage type	Electrical		Mechanical			Electromechanical			Chemical	Thermal
Technologies	Super capacitors	SMES	PHS	CAES	Flywheels	Sodium sulfur	Lithium ion	Redox flow	Hydrogen	Molten salt
Maturity	Developing	Developing	Mature	Mature	Early commercialized	Commercialized	Commercialized	Early commercialized	Demonstration	Mature
Efficiency	90-95%	95-98%	75-85%	70-89%	93-95%	80-90%	85-95%	60-85%	35-55%	80-90%
Response time	ms	<100ms	sec-mins	mins	ms-secs	ms	ms-secs	ms	secs	mins
Lifetime-years	20+	20+	40-60	20-40	15+	10-15	5-15	5-10	5-30	30
Charge time	s - hr	min - hr	hr - months	hr - months	s - min	s - hr	min - days	hr - months	hr - months	hr - months
Discharge time	ms – 60 mins	ms – 8s	1 – 24 hs +	1 – 24 hs +	ms – 15 min	s - hr	min - hr	s - hr	1 – 24 hs +	min - hr
Evirnomental impact	None	Moderate	Large	Large	Almost none	Moderate	Moderate	Moderate	Depends on H2 production method	Moderate

Source: World Energy Council, *Five Steps to Energy Storage: Innovation Insights Brief*, London, U.K., 2020, p.9.

H2 Hydrogen
RES Renewable energy source
SMES Superconducting magnetic energy storage
RE Renewable energy
PHS Pumped hydroelectric storage
CAES Compressed-air energy storage

Table 4: Overview of possible applications by selected energy storage technologies

Storage Principle		Electrical		Mechanical			Electromechanical			Chemical	Thermal
Technologies		Supercapacitors	SMES	PHS	CAES	Flywheels	Sodium sulfur	Lithium ion	Redox flow	Hydrogen	Molten salt
Possible applications	Power quality	Proven	Proven			Proven	Proven	Proven	Promising		
	Energy arbitrage			Proven	Proven	Promising	Proven	Proven	Proven	Promising	Proven
	RES integration		Proven			Proven	Proven	Proven	Proven	Proven	
	Emergency backup					Proven	Proven	Proven	Proven	Promising	
	Peak shaving			Proven	Proven		Proven	Proven	Promising	Promising	Promising
	Time shifting		Proven	Proven	Proven		Proven	Proven	Promising	Promising	Promising
	Load levelling			Proven	Proven		Proven	Proven	Promising	Promising	Promising
	Black start						Proven	Proven	Proven	Promising	Promising
	Seasonal storage			Promising	Possible					Promising	Promising
	Spinning reserve		Promising			Promising	Proven	Proven	Promising	Promising	
	Network expansion			Proven	Promising		Proven	Proven	Promising	Promising	Promising
	Network stabilization	Promising	Proven			Promising	Proven	Proven	Promising		
	Voltage regulation	Promising	Promising			Promising	Proven	Proven	Proven		
	End-user services	Promising	Promising			Promising	Proven	Proven	Promising		

Source: World Energy Council, *Five Steps to Energy Storage: Innovation Insights Brief*, London, U.K., 2020, p.9

H2 Hydrogen
RES Renewable energy source
SMES Superconducting magnetic energy storage
RE Renewable energy
PHS Pumped hydroelectric storage
CAES Compressed-air energy storage

Proven **Promising** **Possible**

Thermal energy storage

The transition to renewables needs long-duration storage, particularly at night once coal and fossil gas exit the system. Batteries are good for short-duration storage, ranging from mere minutes to an hour or two. But a lot of batteries are needed, at enormous cost, to deliver 8-12 hours of electricity.

TES technologies convert electricity to heat and store it until it is needed – hours, days, or months later – by industries/factories, buildings, or even towns. TES can help to decouple heating and cooling demand from immediate power generation and supply availability, to balance seasonal demand, to reduce the need for costly grid reinforcements, and to support the transition to a renewable-based energy system.[103]

There are three categories of thermal energy storage technologies (Table 5):[104]

1. **latent heat storage** - a phase-change process deploying salts, polymers, gels, paraffin waxes and metal alloys.[105]
2. **sensible heat storage** - a process where the temperature of the storage medium such as molten-salt, hot rocks or concrete, hot silicon, either increases or decreases.[106]
3. **thermochemical heat** - a process of reversible exotherm/endotherm chemical reaction with thermo-chemical materials, such as adsorption or sorption solar heating and storage technology, salt hydrate technology, and molecular bonds.[107]

Table 5: Comparison of the three categories of thermal energy storage

Categories	Sensible	Latent	Chemical
Storage medium	• Water, gravel, pebble, soil	• Organics, inorganics	• Metal chlorides, metal hydrides, metal, oxides
Type	• Water-based system (water tank, aquifer)	• Active storage	• Thermal-sorption (adsorption, absorption)
Advantage	• Environmentally friendly cheap material • Simple system, easy to control • Reliable	• Higher energy density than sensible heat storage • Provide thermal energy at constant temperature	• Highest energy density, compact system • Negligible heat losses
Disadvantage	• Low energy density, huge volumes required for district heating • Self-discharge and heat losses • High cost of site construction • Geological requirements	• Lack of thermal stability • Crystallization • Corrosion • High cost of storage material	• Poor heat and mass transfer property under high-density condition • Uncertain cyclability • High cost of storage material
R&D status	• Large-scale demonstrations	• Material characterization • Lab-scale prototypes • Demonstrations	• Material characterization • Lab-scale prototypes

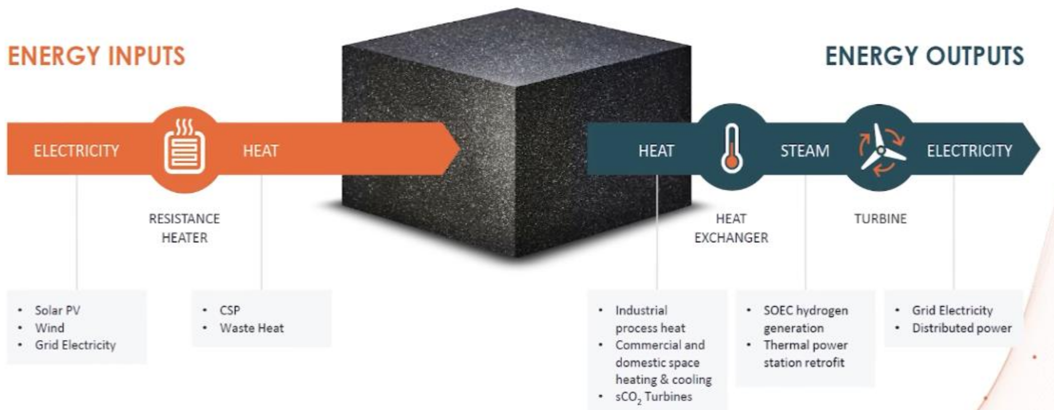
Adapted from: Kalaiselvam, S., and R. Parameshwaran, 'Thermal Energy Storage Technologies', in *Thermal Energy Storage Technologies for Sustainability*, S. Kalaiselvam and R. Parameshwaran, eds., Academic Press, 2014, pp. 57-64, doi: 10.1016/B978-0-12-417291-3.00003-7.

Thermal storage technology: Miscibility Gaps Alloy

Miscibility Gaps Alloy (MGA) technology is a ground-breaking patented zero-carbon renewable energy storage for grid and industrial use. The MGA is a new type of phase-change thermal storage material with high thermal conductivity that can receive energy generated by renewables, storing it cheaply and safely as thermal energy.[108] During these transitions, heat can be added or extracted without affecting the material’s temperature, giving it an advantage over the sensible heat storage technologies. Figure 16 illustrates how the MGA thermal storage works.

Developed at the University of Newcastle in Australia, the MGA technology has the potential to be a cost-effective, medium-duration storage technology.[109] As coal power stations shut down, the critical need is for medium duration (4 to 12 hours) storage to manage daily variations in solar and wind output to meet demand.[110]

Figure 16: The MGA thermal energy solution

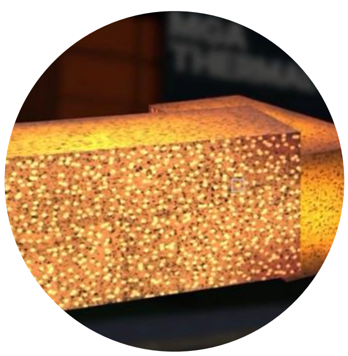


Source: Building Blocks for Energy Storage: MGA Thermal tour, Engineering with Rosie, <https://youtu.be/KpYFdUc1ot0>.

Three brief introductory videos of MGA technology are available below:

- https://youtu.be/4Y-y4P1VAcM
- https://youtu.be/SErKLPShj-o
- https://youtu.be/bt-Ux48Aohw

MGA blocks



The MGA blocks are literally the building blocks of the MGA thermal energy storage system. The blocks are made from a high-conductivity matrix featuring MGA, and a phase-change material composed of a series of metal alloys dispersed throughout the matrix as particles, which release and store energy as they are heated and cooled, shifting from solids to liquids.[111] With the MGA matrix holding the particles in place, electricity produced from renewable sources can be pumped into the bricks, allowing the particles to melt and store energy, then cool and release energy.[112]

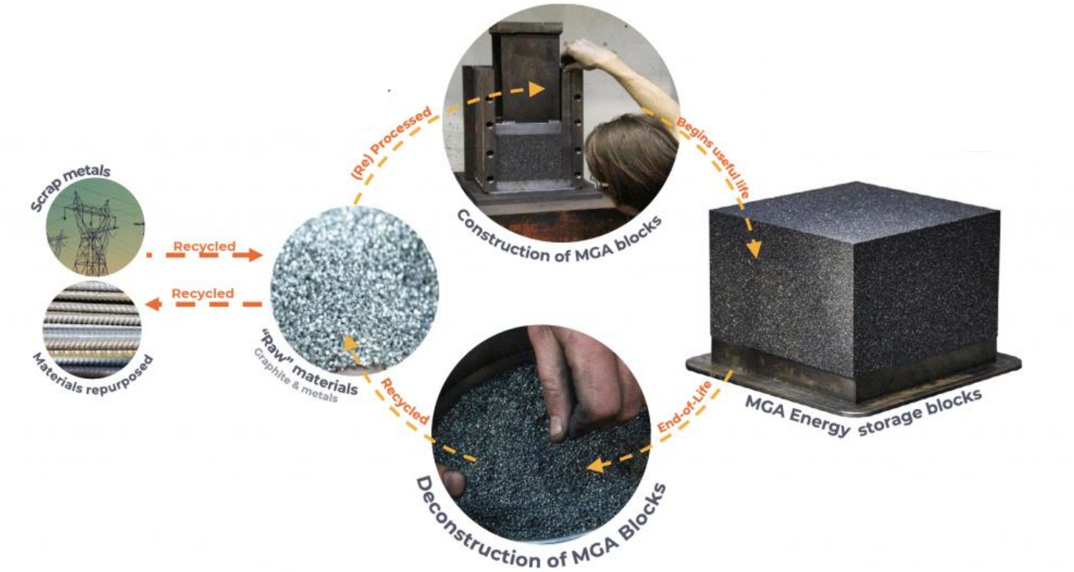
The MGA team likens the thermal storage process to a choc-chip muffin being heated in the microwave where the matrix is the cake component that holds everything in shape when heated and rapidly distributes that heat.[113] The other particles, represented by the choc-chips, melt and store thermal energy through the solid to liquid change phase.[114] Unlike a choc-chip muffin, a MGA block can undergo the process of heating, storing energy, cooling and recovering energy thousands of times.

The source of energy could be concentrated heat from the sun, surplus electricity on the grid, renewable energy, or industrial heat or waste heat. The blocks can store heating water to form steam. The blocks can be designed with internal tubing or interact with other heat exchangers so that when water is pumped in, superheated steam is formed.[115]

Features and benefits

- The MGA blocks are 20cm x 30cm x 16cm, making them highly transportable. They are stackable like LEGO® and can be added or removed to scale the system up or down to meet market demand. Their modular feature means that they can be used in a range of environments and to power facilities of varying sizes.
- With potential deployments for industrial heating, the TES MGA system could help decarbonize the electricity grid and heavy industries.
- The MGA blocks are cheaper, safer, last much longer than batteries. They are 10 per cent of the cost of a lithium battery of the same size and yet produce the same amount of energy.[116] There is no risk of explosion or combustion in hazardous environments, that can happen with batteries.
- Experiments have shown that the blocks can store millions of kilowatt hours of energy and offers near to 100 per cent conversion of electricity to heat and the lowest levelised cost of storing electricity - a measure of the total lifecycle cost of a facility compared to the amount of energy it can store.[117]
- The MGA block is a circular innovation. Resource recovery and material availability are core to product development and manufacturing. Figure 17 illustrates the MGA block lifecycle. The blocks are made from non-toxic, 100 per cent recyclable material that can be recycled at the end of their long lifetime.[118] MGA blocks can be made using recycled materials.

Figure 17: MGA is designed for the circular economy.



Source: MGA Thermal <www.mgathermal.com>

The MGA team is conducting two projects to validate the technology as part of its pathway to commercialization.

Project 1

This project (May 2022 to April 2024) will design, manufacture, and operate a 0.5 MW_{th} / 5 MWh_{th} demonstration scale thermal energy storage facility.[119] The aim is to validate the technical performance of MGA Thermal's proprietary technology under a variety of end-use case simulations and improve the business case for MGA Thermal's technology in comparison to competing energy storage technologies.[120] The MGA demonstration unit will be roughly the size of a shipping container and will have 5000 MGA blocks, which if entirely converted into electricity, will power about 600 homes for 10 hours.[121]

Project 2

This project (started Oct 2022) tests the feasibility of a thermal battery to power a 200 MW generating unit at a power station for eight hours and the viability of repurposing power stations for renewable thermal energy storage technology.[122] It examines the potential of the MGA technology to address three challenges to energy transition:

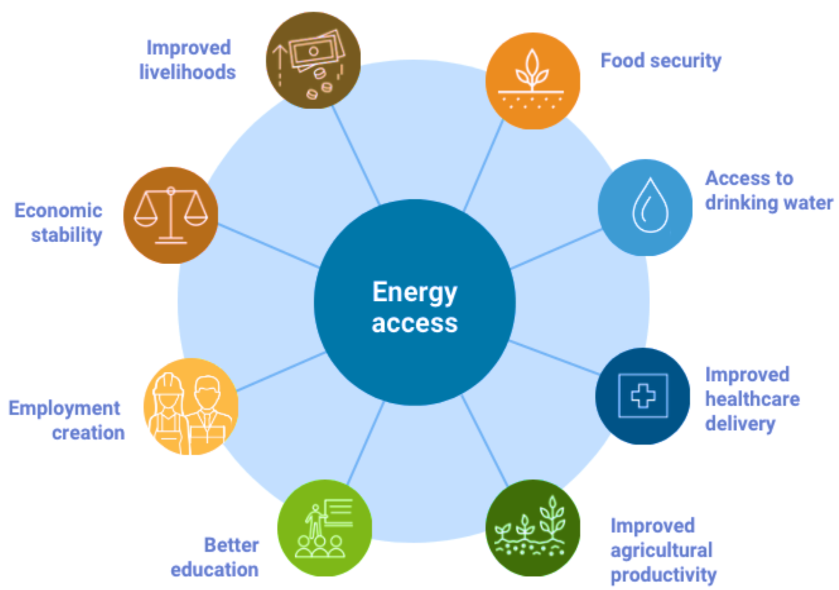
- the impact of intermittent power caused by many distributed renewable power sources and fluctuating load demand and power supply,
- the potential impact on the local economy and workforce when fossil fuel power plants shut down, and
- what to do with the 'bricks and mortar' investments in power plants and transmission infrastructure.

Conventional power grids are not designed to receive large spikes associated with renewable energy. The cost of redesigning the whole grid to integrate multiple sources of renewable energy is expensive. The cost of decommissioning a power plant is equally high. By putting existing infrastructure to use, the MGA TES system could help deliver renewable energy at grid-scale regardless of the intensity of sun or wind. This will help fossil fuel power stations gradually transition to coal-free operation and to become renewable power stations.

6. Potential impacts

The transition to and availability of clean, reliable and affordable energy services will contribute to climate change mitigation and disaster risk reduction and accelerate the realization of multiple social and economic benefits for underserved communities and children and young people. Figure 18 identifies the key social and economic benefits. Table 6 (p.55) summarizes the ways in which renewable energy technologies power up multiple SDG results for children. Table 7 (p.56) reviews the potential of next generation solar PV technologies for the humanitarian and development sector. Table 8 (p.57) puts forward some potential applications of novel renewable energy innovations for the humanitarian and development sector.

Figure 18: Social and economic benefits of renewable energy access for vulnerable communities and in humanitarian and development settings



Source: IRENA, Universal access to energy is vital for global development, 2023, <www.irena.org/Digital-content/Digital-Story/2023/Jan/How-decentralised-renewable-solutions-improve-livelihoods-in-vulnerable-communities/detail>.

Table 6: Renewable energy technologies power up multiple SDG results for children

No poverty

- Access to clean, reliable energy can strengthen delivery of social services for children, reduce multidimensional poverty, build resilience and sustain development gains - especially in areas subject to shocks and chronic stress.[123]

Good health and wellbeing

- Decentralized and reliable energy at healthcare facilities can power vital life-saving medical equipment 24/7 (e.g., vaccine refrigerators, diagnostic equipment, ventilators, emergency and operating rooms), ensure access to maternity treatments, safe births any time of day, postnatal care and reproductive health, and improve facility operations and staff retention.
- Electricity provides lighting, heating, cooling, digital connectivity and clean water.
- The cooking electrification reduces indoor air pollution and can improve nutrition of children.[124]

Quality education

- Modern, reliable and affordable electricity at schools, learning centres and homes increase school attendance; allow for longer operating hours; improve educational outcomes and students' quality of learning; and support remote learning and studying outside of daylight hours.
- Electricity is also associated with teacher retention.[125]

Gender equality

- Sustainable energy solutions can empower girls and young women by increasing school attendance and the ability for home study.
- It can also save them time and effort from having to travel far to collect water and fuelwood, provide safety at night, and boost technical skills-building and livelihood opportunities.[126]
- The renewable energy economy opens opportunities for women to become energy entrepreneurs.

Clean water and sanitation

- Accessible and affordable energy is needed for reliable water supply and purification.
- Consistent, climate-resilient water supply systems in communities powered by solar or other renewable energy sources help ensure access to sustainable, affordable, equitable and safe water services.
- Solar-powered water pumps can contribute to improving agriculture productivity and food security.
- Keeping water safe and accessible can lessen children's exposure to deadly waterborne diseases.[127]

Affordable and clean energy

- Sustainable energy solutions can help achieve better health, education, safe water and sanitation, and social policy outcomes in development and humanitarian situations for the most vulnerable children and young people.[128]

Decent work and economic growth

- Sustainable energy solutions can increase opportunities for full and productive employment and decent work for young people, especially in technical skills training as the renewable energy market grows.[129]

Climate action

- Sustainable energy solutions in child-centric social sectors can contribute to reducing greenhouse gas emissions and air pollution, promote climate-resilient development and disaster recovery, and increase green job opportunities.[130]

Table 7: The potential of next generation solar PV technologies for the humanitarian and development sector

Next gen solar PV	TRL*	Key features	Constraints	Potential applications for the humanitarian and development sector
Perovskite	4-6	• The fastest-improving solar technology in terms of power-conversion efficiencies. • Lightweight and much less expensive to produce than silicon. • Easier to make than silicon cells. • Can be semi-transparent and wrapped around uneven surfaces • Can be printed with inkjet printers.	• Long-term instability involving external factors, such as water, light, and oxygen and intrinsic instability due to heating. • Susceptible to degradation through extrinsic factors, such as moisture, oxygen, heat and light. • Most efficient perovskites are based on metal halides (lead) and moving beyond this has proved challenging.	• Lightweight mobile solar modules to generate electricity off-grid or as microgrid in emergencies, for rooftop installation (much lighter than silicon panels), solar water pumps, and agrivoltaics. • Contribute to 'build back greener' post-conflict and post-disaster reconstruction and recovery through building-integrated PV. • PV cell-driven battery
Organic PV (OPV)	3-4	• Made with compounds that are dissolved in ink and printed onto thin plastics. • Compared to silicon, production methods for OPVs are low-cost and environmentally friendly. • Tunable electronic properties, low material toxicity and low environmental impact. • Can be semi-transparent	• Pathway to commercialization is currently constrained by stability issues which shorten the device lifetime. • Vulnerable to moisture and oxygen. The problem can be fixed by incapsulating the cell, but this adds to the production cost, unit weight and reduces efficiency.	• Smart windows for greenhouses, supporting livelihood, food security, and generating electricity for rural and remote households. • Energy harvesting to power wearable electronics and diagnostic and monitoring biomedical devices • Integrate into clothing to generate heat in the cold (winterization products) for newborns and children.
Quantum dots PV	3-4	• Theoretically, quantum dot PVs would be cheaper to manufacture because they are made through chemical reaction. • Enhance the efficiency and scalability of perovskite PV. • Flexible and can be printed at a large scale with inkjet printing and spin coating processes • Energy range is tunable by changing the dot size	• In real world use, Quantum dot PVs lag the efficiency of standard solar cells. • Cadmium selenide-based quantum dot solar cells are highly toxic and require very stable polymer shells. • Often lose performance when exposed to ambient air and are sensitive to raised temperatures and moisture.	• QD PV can convert passive buildings into energy generation units, and reduce the heat of the building. • Power electronic devices (in disasters and humanitarian situations) and wearable biosensors for healthcare monitoring.

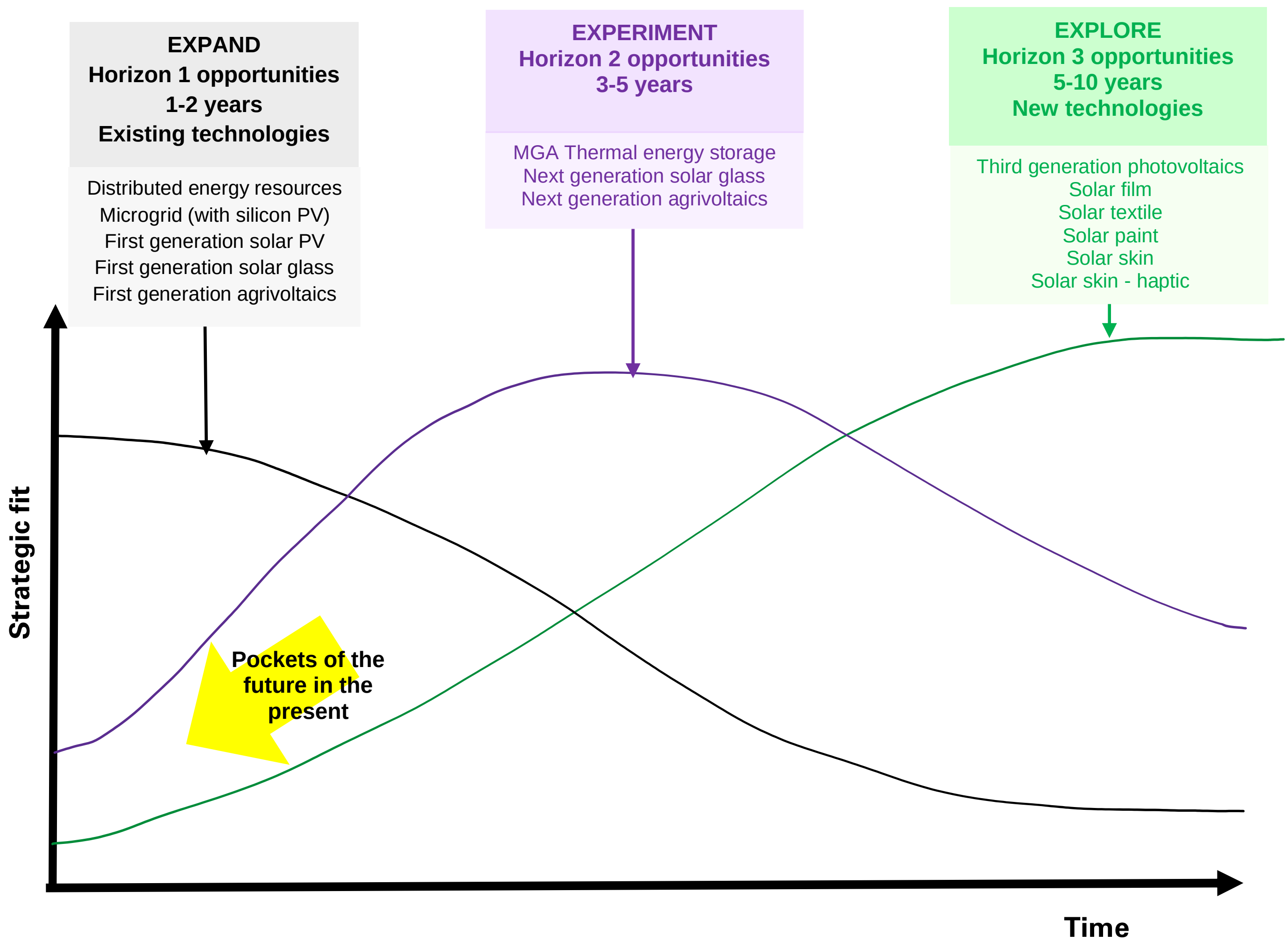
*Technological Readiness Level. See Appendix (p.66) for an explanation of the TRL scale.

Table 8: The potential applications of novel renewable energy innovations for the humanitarian and development sector

Emerging innovations		TRL	Potential applications in the humanitarian and development sector
Quantum computing for distributed energy resources		2-3	• Solve complex optimization problems of demand and distribution management in distributed renewable energy systems. • Grid safety and resilience, and cybersecurity. • Climate modeling and weather forecasting. • Accelerate discovery and development of new energy production and storage technologies.
MGA thermal storage		7	• Can power facilities of varying sizes and environments due to its modular design. • Retrofit and repurpose decommissioned power stations for renewable energy storage, unlocking opportunities to leverage decommissioned or soon to be decommissioned assets globally, turning a liability into a high value asset. • Transition the local economy and build the local workforce for renewables
Novel solar innovations enabled by third generation solar cell technologies	Solar film	5	• Can be deployed in disaster relief and recovery where power is needed quickly & temporarily. • Printed solar film can be used for roof-top solar energy system in low-income countries. • Retractable recharging systems for electric vehicles, caravans/camping and rooftop of vehicles • Floating solar market (a rapidly growing market in Asia). • Floating covers for dams to reduce water evaporation and generate electricity. • Integration into building products, like roofing materials and smart blinds, and portable products, e.g., in a laptop bag to charge a computer on the go.
	Solar paint	3-4	• Can be deployed to coat almost any surface and existing structure to generate energy. • Hydrogen solar paint is adaptable to a range of climates, even remotes areas far from water. • Can be integrated when building infrastructure such as roadways and parking lots, thereby leveraging opportunities to generate renewable energy in large-scale development projects.
	Solar glass	8-9	• Can be integrated into a building and roofing systems and perform effectively in locations and conditions where traditional silicon panels cannot. • Greenhouse - solar glass to provide power to run heating or cooling for greenhouses, as well as desalination to provide water. • Agrivoltaics - solar glass can be tailored to suit the growing conditions for particular plants, turning deserts into productive agricultural land. The global agrivoltaic market is expected to increase significantly due to limited availability of land for cultivation and the climate crisis.
	Solar textile	4	• Solar tents can be used in climate and humanitarian emergencies when power needs to be deployed rapidly to meet the needs of the most vulnerable. • Solar filaments can be woven into the fabric for winter coat, gloves, or other piece of clothing. • Can be used for solar canopies, solar tarpaulin, solar tents and awnings to capture and store energy for outdoor lighting in remote areas to improve safety of women and children at night. • Use as shade sails in car parks in urban areas, generating electricity to local communities.
	Solar skin	4	• Solar skins that have pass stringent fire and building safety regulations can be integrated into construction materials to allow solar PV to be used to encase a building. It could be useful for 'build back greener' in post-conflict and post-disaster recovery and reconstruction. • Affordable and reliable electricity in remote communities and humanitarian emergencies.
	Solar skin - haptic	4	• Solar skin (haptic) is a breakthrough that could help create cheaper and better prosthetics, transforming the lives of people with disabilities and victims of conflict. Solar skin prosthetics could potentially enable a wide range of motion, including grasping and moving items that are currently too small to do with finesse, such as moving a computer mouse.

By mapping solar technologies along the three horizons of innovation, immediate opportunities can be identified, and future potentials envisioned. Innovation can lose the 'fit' over time as the external environment changes. The global community should stay open to and make sense of emerging options that could lead to transformational change.

Figure 19: The three horizons of innovation



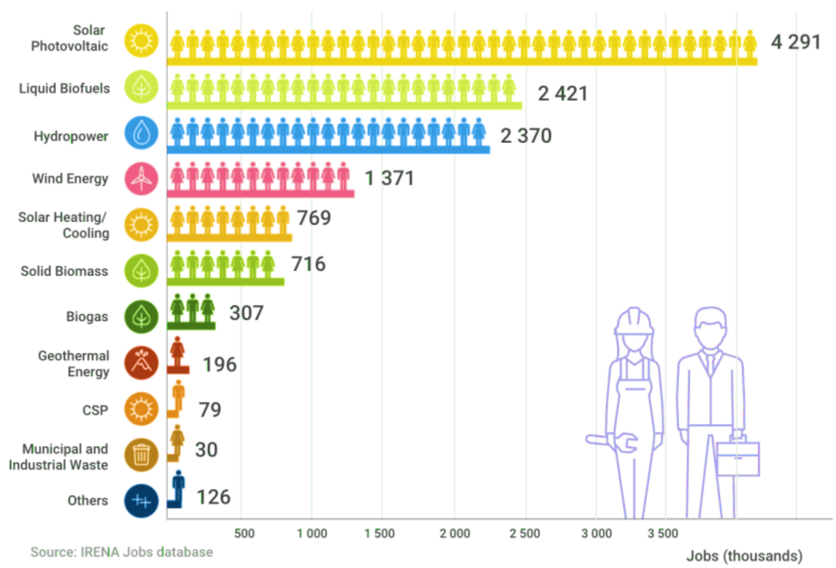
Renewable energy create green jobs

Jobs in renewables are forecast to reach 42 million globally by 2050, four times their current level, through the increased focus of investments on renewables. Energy efficiency measures are forecast to create 21 million jobs, with an additional 15 million jobs estimated to be created from system flexibility needs.[131]

In 2022, worldwide employment in the renewable energy sector is 12.7 million, up from 12 million in 2021.[132] The fastest-growing sector is solar photovoltaic 4.3 million jobs (Figure 19).[133] The International Labour Organization (ILO) and the IRENA claim that with front-loaded investments for energy transition, the number of jobs in the energy sector could rise to 139 million in 2030, including more than 74 million in energy efficiency, electric vehicles, power systems and hydrogen.[134]

Green jobs and the pathway for a just green transition that they can enable are vital for young people. Preparing today's children for tomorrow's opportunities through education, entrepreneurship and empowerment underpins the UNICEF, ILO and United Nations Environment Programme (UNEP) Green Jobs for Youth Pact.[135] The pact aims to create 1 million new green jobs with existing employers, assist in the greening of 1 million existing jobs, and support 10,000 young green entrepreneurs to set up sustainable businesses.

Figure 19: Global renewable energy employment by technology



Source: IRENA and ILO, Renewable energy and jobs: Annual review 2022, International Renewable Energy Agency, Abu Dhabi and International Labour Organization, Geneva, 2022.

Note: Data are principally for 2021, with some dates for 2020 and a few instances in which only earlier information is available. The data for hydropower include direct employment only and for other technologies include both direct and indirect employment wherever possible. 'Other Technologies' include jobs not broken down by individual renewable energy technologies.

Trade-offs

The global transition to renewable energy has magnified the challenge to balance human rights and environmental and biodiversity protection with the need to provide clean and affordable energy to all and to reduce the impact of climate change.[136] Table 9 outlines some of the trade-offs that need to be minimized and appropriately managed the potential risks as the transition to renewable energy accelerates.

Table 9: Potential adverse impacts of renewable energy

Renewable energy	Potential adverse impacts
Solar energy	• Large utility-scale solar facilities (solar thermal plants) can raise concerns about land degradation and habitat loss. • The PV cell manufacturing process includes hazardous materials. The amount and type of chemicals used depends on the type of cell.
Wind energy	• Offshore wind farm developments can have a substantial impact on the structuring of coastal marine ecosystems on basin scales.[137] • Potential impacts on local ocean dynamics and the structure of the marine ecosystem.
Hydropower	• Potential loss of biodiversity and agricultural land. • Displaces local communities. • the creation of hydropower reservoirs leads to an initial increase in greenhouse gas emissions from the decomposition of organic matter.
Geothermal energy	• May emit carbon dioxide, silica, methane, ammonia, and sulfur dioxide, and depending upon the depth and location of the reservoir, some may contain lethal substances such as boron, mercury, and arsenic. • Can have impacts on both water quality and consumption.
Bioenergy	• Energy created by burning biomass creates greenhouse gas emissions, but at lower levels than burning fossil fuels. • Negative environmental impacts related to large-scale increases in forest and bioenergy plantations, resulting deforestation and land-use change.
Ocean energy	• Disturb the ocean's ecosystems. • Equipments used to capture this ocean energy can disrupt and destroy marine life.

Renewable technologies can also create ethical challenges along the supply chain and product life cycle.

The environmental and human rights impact of critical mineral extraction

The transition to a zero-carbon world will need a sixfold increase in the extraction and production of critical minerals such as copper, lithium, nickel, cobalt by 2030.[138] PV cells require silver, copper and myriad of mineral and sometime toxic metals. EV batteries need lithium, cobalt and nickel.

The Business and Human Rights Resource Centre's Transitions Mineral Tracker monitors the practices of companies mining six commodities vital to the clean energy transition: cobalt, copper, lithium, manganese, nickel and zinc.[139] From 2010 to 2021, the tracker identified 495 allegations of human rights abuse, including child labour, and a third of attacks against Human Rights Defenders and against Indigenous peoples.[140] Communities may also be exposed to high-level environmental health risks caused by extensive mining activities. The environmental impacts also include water pollution and wildlife and species habitat destruction.[141]

Development-induced displacement

While the building reservoirs for hydropower, mining critical mineral and wind turbines can bring enormous benefits to communities, the gains are often unevenly distributed. They impose costs that are usually borne by the most vulnerable members of these communities. Some are forced to leave their homes to make way for large scale renewable energy projects. Their livelihood is disrupted and they face serious long-term risks of becoming more vulnerable economically and dislocated socially.

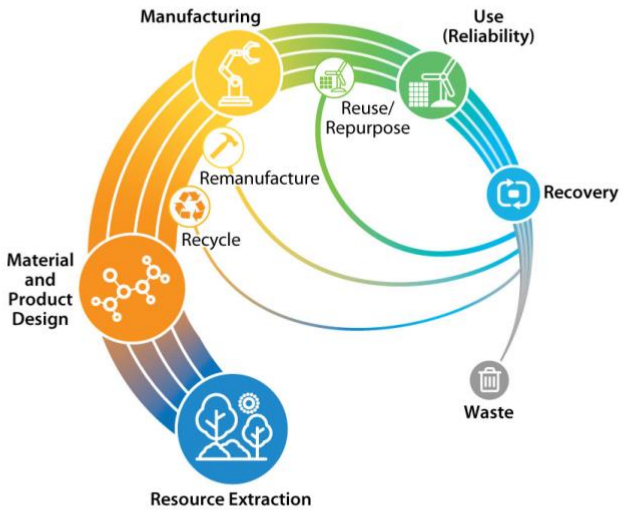
Solar panel waste

The global growth of the PV will increase the volume of decommissioned PV panels. IRENA estimates that large amounts of annual waste are anticipated by the early 2030s and could total 78 million tonnes by 2050.[142]

Statistical modelling on solar waste published in the Harvard Business Review claims the probability of PV waste is likely to be 50 times more than IRENA's estimation because the replacement rate of solar panels is faster than expected.[143] The problem of solar waste is worsened by the high cost of recycling, which means most panels go to landfill.[144] There is a lack of assessment of the likely short and long term effects of toxic heavy metal leachate risk that large-scale PV solar presents on land and river systems.

Good practices for end-of-life PV management are urgently needed. Although the research on solar panel reuse and recycling is only nascent, there are some promising developments. Research is currently underway to explore the use of microbes to recover metals from e-waste.[145] The challenge to closing the loop in material lifecycle will present opportunities to ensure the energy transition is as sustainable and circular as possible (Figure 21). As PV demand increases, identifying and developing the technical, economic, and regulatory requirements for a PV circular economy will be needed.[146] This will involve everyone across the PV value chain. For LICs, a cost-effective alternative could be to refurbish, repurpose, repower solar panels for their 'second life'.

Figure 21: Circular economy for energy material



Source: NREL: Transforming energy. Circular Economy for Energy Materials, < https://www.nrel.gov/research/circular-economy.html>.

07

7. Conclusion

Renewable energy, solar technologies and the race to zero

This Insight Report has highlighted the importance of transitioning to renewable energy and explored the potential of emerging solar technologies to provide affordable, reliable and clean energy to all while reducing GHG emissions. Renewable energy sources are available in all countries but their potential is yet to be fully harnessed. Scientists and researchers working in the area of solar technologies are seeking to increase energy efficiency while reducing the production and consumer costs. Emerging solar technologies have multiple end-uses that are beyond electricity generation in the conventional sense.
Both the IPCC and IEA have concluded that the path to net-zero emissions requires huge leaps in clean energy innovation. The technologies that are effective today may be much less effective in the longer term due to shifting conditions.

Child-sensitive and climate-resilient development

Where sustainable energy access is lacking or unreliable, children and young people pay the biggest price as they are one of the most-affected groups due to lack of energy access. Over a billion children are already at extremely high risk of environmental and climate hazards including heat waves, floods, and droughts. These impacts threaten to undermine decades of progress on every child's ability to survive, grow and thrive.

Affordable and clean electricity is an important enabler that strengthens social services to improve young lives. It improves the quality, accessibility and reliability of essential services such as education, universal healthcare and safe water and sanitation and aid in advancing development goals and reducing multidimensional poverty. The transition to affordable and accessible renewable energy, especially solar, is one of the best investments that can be made to reduce the risks from climate change and to ensure a liveable planet for children.

Appendix: Technology Readiness Levels (TRL)

The TRL Scale is a globally accepted benchmarking tool for tracking progress and development of a specific technology from basic research to systems demonstration in expected operating environment.

Technology development stage	TRL	Definition
Green field research	0	Initiated with a novel idea, guiding question, or poking at a problem from new angles.
Fundamental - basic Research	1	Basic principles observed and reported. The work is analytical with the emphasis on understanding the science better.
	2	Technology and/or application concept formulated. Scientific research begins to be translated into applied research and development.
Research and Development	3	Research to prove feasibility. Analytical and experimental critical function and/or characteristic proof of concept.
	4	Technology development. Validation of component(s) in a laboratory environment
	5	Validation of semi-integrated component(s) in a simulated environment
Pilot and Demonstration	6	Technology demonstration. Engineering/pilot-scale, similar (prototypical) system and/or process validation in relevant simulated environment.
	7	Prototype system ready (form, fit and function) demonstrated in an appropriate operational environment. Final design is virtually complete.
	8	Actual technology completed and qualified through tests and demonstrations.
Early Adoption (small scale)	9	Actual technology proven through successful deployment in an operational environment. The technology is in its final form and operated under the full range of operating mission conditions.
Commercial trail (Small scale)		

Endnotes

[1] International Panel on Climate Change, *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change,* Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 2023.

[2] Ibid., p.70.

[3] Ibid., p.61.

[4] United Nations, Committee on the Rights of the Child, General comment No. 26 (2023) on children's rights and the environment, with a special focus on climate change, CRC/C/GC/26 (22 August 2023).

[5] UNICEF, *Climate, Energy, Environment and DRR (CEED) in UNICEF's 2022-2025 Strategic Plan*, <www.unicef.org/media/124226/file/CEED%20themes%20in%20UNICEF's%202022-2025%20Strategic%20Plan.pdf>, accessed 29 April 2023. See also United Nations Children's Fund - Climate, Environment, Energy and Disaster Risk Reduction, *A brighter life for every child with sustainable energy*, UNICEF, New York, USA, 2023.

[6] The International Energy Agency has two extensive databases of clean energy technologies. 1) Clean Energy Demonstration Projects Database <www.iea.org/data-and-statistics/data-tools/clean-energy-demonstration-projects-database>. The Database maps major demonstration projects of clean energy technologies globally. 2. ETP Clean Energy Technology Guide <www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide>. The Guide contains information for over 500 individual technology designs and components across the whole energy system that contribute to achieving net-zero emissions.

[7] United Nations, *The Sustainable Development Goals Report 2022*. New York: United Nations Department of Economic and Social Affairs, 2022. p.40.

[8] Pierre Friedlingstein et al., 'Global Carbon Budget 2022', *Earth System Science Data*, vol. 14, no. 11, 2022, doi:10.5194/essd-14-4811-2022.

[9] U.S. Energy Information Administration. *The International Energy Outlook 2021*, <eia.gov/outlooks/ieo/introduction/sub-topic-02.php>, accessed 01 Feb 2023.

[10] United Nations, *The Sustainable Development Goals Report 2022*, United Nations Department of Economic and Social Affairs, New York, 2022. p.40.

[11] Ibid., p.14.

[12] UNICEF, *Clear the air for children. The impact of air pollution on children*. UNICEF, New York, 2016.

[13] World Health Organization, *Energizing health: accelerating electricity access in health-care facilities*, World Health Organization, Geneva, 2023.

[14] United Nations. *Policy Briefs in Support of the High-Level Political Forum 2022. Addressing Energy's Interlink with other SDGs*, United Nations Department of Economic and Social Affairs, New York, 2022.

[15] Ibid.

[16] UNICEF, *Key asks for 2020 SDG Voluntary National Reviews: SDG 7*, <www.unicef.org/media/138096/file/SDG%207%202023%20rev.pdf>, accessed 02 May 2023.

[17] Kam, V., et al., 'Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem', *Environmental Research*, vol. 195, 2021, doi: 10.1016/j.envres.2021.110754.

[18] Xue, T., 'Estimation of stillbirths attributable to ambient fine particles in 137 countries', *Nature Communications*, vol. 29, no. 13, 2022, doi: 10.1038/s41467-022-34250-4. This first global analysis follows discovery of toxic pollution particles in lungs and brains of foetuses and covers 137 countries in Asia, Africa,

and South America, where 98% of stillbirths occur. The work was based on data from more than 45,000 stillbirths and live births.

[19] United Nations Inter-agency Group for Child Mortality Estimation (UN IGME), *A Neglected Tragedy: The global burden of stillbirths*, United Nations Children's Fund, New York, 2020.

[20] Ritchie, H., M. Roser and P. Rosado, 'Energy', 2022, <https://ourworldindata.org/energy>, accessed 01 Feb 2023.

[21] United Nations, Causes and Effects of Climate Change <www.un.org/en/climatechange/science/causes-effects-climate-change>, accessed 01 Feb 2023.

[22] Ritchie, H., M. Roser and P. Rosado, 'Energy', 2022. Note that Ritchie, Roser and Rosado define renewable energy as hydropower, solar, wind, geothermal, wave, tidal and modern biofuels but exclude traditional biomass – which can be an important energy source in lower-income settings.

[23] United Nations, *Policy Briefs in Support of the High-Level Political Forum 2022. Addressing Energy's Interlink with other SDGs*, 2022, p.8.

[24] World Bank, *World Development Indicators* (2022.05.26) <https://datacatalog.worldbank.org/search/dataset/0037712/World-Development-Indicators>, accessed 02 Feb 2023.

[25] Energy is the capacity for doing work. It may exist in potential, kinetic, thermal, electrical, chemical, or nuclear. Energy cannot be created nor destroyed. It can only be changed from one form to another. Electricity is a form of energy. It is the physical phenomena arising from the behavior of electrons and protons that is caused by the attraction of particles with opposite charges and the repulsion of particles with the same charge.

[26] UNICEF, The UNICEF Sustainability and Climate Change Action Plan 2023-2030, UNICEF Programme Group, New York, Sep 2023.

[27] United Nations, *Global Roadmap for Accelerated SDG7 Action in Support of the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change* <www.un.org/sites/un2.un.org/files/2021/11/hlde_outcome_-_sdg7_global_roadmap.pdf>, accessed 12 February 2023; United Nations High-level Dialogue on Energy <www.un.org/en/conferences/energy2021>, accessed 12 February 2023; United Nations Energy Compacts <www.un.org/en/energycompacts>, accessed 12 February 2023.

[28] United Nations, Climate Action - Renewable Energy <un.org/en/climatechange/what-is-renewable-energy>, accessed 12 Feb 2023.

[29] International Energy Agency, *Renewables 2022, Analysis and forecast to 2027*, IEA, Paris, 2021, p.21.

[30] Stanford University <web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/100PercentPaperAbstracts.pdf>, accessed 06 May 2023.

[31] Ibid.

[32] Ibid.

[33] LCOE is the cost of building the power plant itself and the ongoing costs for fuel and operating the power plant over its lifetime.

[34] International Renewable Energy Agency, *Renewable Technology Innovation Indicators: Mapping progress in costs, patents and standards*, IRENA, Abu Dhabi, 2022 [previous: United Nations, Climate Action - Renewable Energy, <www.un.org/en/climatechange/what-is-renewable-energy>, accessed 12 Feb 2023].

[35] Vezzoli, C., et al., *Designing Sustainable Energy for All. Green Energy and Technology*, Springer, Cham., 2018, doi: 10.1007/978-3-319-70223-0_2, p.9.

[36] IRENA's new report *Off-grid Renewable Energy Statistics 2022* provides statistics for the period 2012–2021 covering mini-grids, biogas for cooking and lighting, off-grid solar lights, pumps, and home solar systems across Africa, Asia, Central and South America, Oceania, the Middle East, and the Caribbean. See, IRENA, *Off-grid renewable energy statistics* 2022, International Renewable Energy Agency, Abu Dhabi, 2022.

[37] Australian Renewable Energy Agency < https://arena.gov.au/renewable-energy/distributed-energy-resources>, accessed 10 February 2023.

[38] World Bank - Energy Sector Management Assistance Program. *Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers* - ESMAP Technical Report 014/19, World Bank, Washington, DC. 2019.

[39] See Andersen, U. L., 'Photonic chip brings optical quantum computers a step closer', *Nature*, vol. 591, pp.40–41, 2021, doi: 10.1038/d41586-021-00488-z; Giani, A., and Z. Eldredge, 'Quantum computing opportunities in renewable energy', *SN Comput. Sci*., vol. 2, 393, 2021, doi: 10.1007/s42979-021-00786-3; and Giani, A., and Z. Goff-Eldredge, 'How quantum computing can tackle climate and energy challenges', *Eos*, vol. 103, no. 21, 2022, doi: 10.1029/2022EO220500.

[40] Giani, A., and Z. Goff-Eldredge, 'How quantum computing can tackle climate and energy challenges'.

[41] Paudel, H. P., et al., 'Quantum computing and simulations for energy applications: Review and perspective', *ACS Eng. Au*, vol. 2, no. 3, pp. 151–196, 2022, doi: 10.1021/acsengineeringau.1c00033, and Rice, J. E., et al., 'Quantum computation of dominant products in lithium–sulfur batteries', *J. Chem. Phys.,* vol.154, 134115, 2021, doi: 10.1063/5.0044068.

[42] Giani, A. and Z. Eldredge, 'Quantum Computing Opportunities in Renewable Energy'.

[43] VentureBeat, 'D-Wave's 5,000-qubit quantum computing platform handles 1 million variables', September 2020, <www.venturebeat.com/business/d-wave-advantage-quantum-computing-5000-qubits-1-million-variables>, accessed 9 February 2023.

[44] Infosys Knowledge Institute, 'Quantum Computing - A Game Changer for The Energy and Utilities Sector', Bengaluru: Infosys Knowledge Institute, 2022, <www.infosys.com/about/knowledge-institute/insights/documents/quantum-computing-game-changer.pdf>, accessed 15 February 2023.

[45] Lange, M.A., 'Renewable Energy and Water Resources', in *Climate Vulnerability*, Roger A. Pielke editor, Academic Press, 2013, pp. 149-166. doi: 10.1016/B978-0-12-384703-4.00320-8.

[46] IPCC, *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change*.

[47] El Chaar, L., L. A. Lamont, and N. El Zein, 'Review of photovoltaic technologies', *Renew. Sustain. Energy Rev*. vol. 15, 2011, pp. 2165–2175.

[48] Adeyinka, A., O. Mbelu, and Y. Adediji, 'A review of current trends in thin film solar cell technologies', *World Academy of Science, Engineering and Technology*. *International Journal of Energy and Power Engineering*, vol. 17, no. 1, 2023, pp. 1-10.

[49] Ibid.

[50] Pastuszak, J. and Wegierek, P., 'Photovoltaic Cell Generations and Current Research Directions for Their Development', *Materials*, 2022, vol.15, 5542, doi: org/10.3390/ma15165542.

[51] Singh B.P., Goyal S.K., and Kumar P., 'Solar PV cell materials and technologies: Analyzing the recent developments', *Materials Today Proceedings*, 2021, vol. 3, pp.2843–2849. doi: 10.1016/j.matpr.2021.01.003.

[52] Ibid.

[53] Green, M. A., et al., 'Solar cell efficiency tables (Version 61)', *Prog Photovolt Res Appl*. vol. 31, 2023, pp. 3–16.

[54] Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, 'Perovskite Solar Cells', <https://www.energy.gov/eere/solar/perovskite-solar-cells>, accessed 13 March 2023.

[55] Ibid.

[56] Wilson, G. M., et al., 'The 2020 photovoltaic technologies roadmap', *Journal of Physics D: Applied Physics*, vol. 53, 2020, doi: 10.1088/1361-6463/ab9c6a.

[57] Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, 'Perovskite Solar Cells'.

[58] Ossila, 'Perovskites and Perovskite Solar Cells: An Introduction', <www.ossila.com/pages/perovskites-and-perovskite-solar-cells-an-introduction>, accessed 13 March 2023.

[59] Chandler, D. L., 'Explained: Why perovskites could take solar cells to new heights', MIT News Office <https://news.mit.edu/2022/perovskites-solar-cells-explained-0715>, accessed 10 March 2023.

[60] Ossila, 'Perovskites and Perovskite Solar Cells: An Introduction'.

[61] Ibid.

[62] Shao, JY., et al., 'Recent progress in perovskite solar cells: material science,' *Sci. China Chem.* vol. 66, 2023, pp. 10–64, doi: 510.1007/s11426-022-1445-2.

[63] Snaith, H. J., 'Present status and futures prospects of perovskite photovoltaics', *Nature Materials,* vol. 17, 2018, pp.372-376.

[64] Crow, J. M., 'The search for perovskite durability', *Nature*, vol. 609, S6-S7, 2022, doi: 10.1038/d41586-022-02833-2.

[65] Chandler, D. L., 'Explained: Why perovskites could take solar cells to new heights', 2023.

[66] Snaith, H. J., 'Present status and futures prospects of perovskite photovoltaics'.

[67] Dominik Landerer, D., et al., 'New Directions for Organic Thin-Film Solar Cells: Stability and Performance', *In Micro and Nano Technologies, Advanced Micro- and Nanomaterials for Photovoltaics*, eds., D. Ginley and T. Fix, Elsevier, 2019, pp. 195-244, doi: 10.1016/B978-0-12-814501-2.00009-8.

[68] Ibid.

[69] Ding, L. ed., *Organic Solar Cells: Materials Design, Technology and Commercialization*, Wiley-VCH GmbH, Berlin, 2022, doi: 10.1002/9783527833658.

[70] Dominik Landerer, D., et al., 'New Directions for Organic Thin-Film Solar Cells: Stability and Performance', 2019.

[71] Menke, S. M., et. al., 'Understanding Energy Loss in Organic Solar Cells: Toward a New Efficiency Regime', *Joule*, vol. 2, no. 1 2018, pp. 25–35, doi: 10.1016/j.joule.2017.09.020.

[72] Ibid.

[73] Shenton-Taylor, C., 'What is a quantum dot?', *Voice Magazine - British Council*, August 2019, < https://www.britishcouncil.org/voices-magazine/what-quantum-dot>, accessed 09 March 2023.

[74] Chen, X., et al., 'Perovskite Quantum Dots for Photovoltaic Applications', In: Zhou, Y. and Wang, Y., eds., *Perovskite Quantum Dots*. Springer Series in Materials Science, vol. 303, Springer, Singapore, 2020, pp 243–254, 2020, doi: 10.1007/978-981-15-6637-0_9.

[75] Nozik, A.J. *Quantum Dot Solar Cells*, Paper presented at the NCPV Program Review Meeting Lakewood, Colorado, 2001.

[76] Ibid.

[77] 'Printed solar film', CSIRO, <www.csiro.au/en/work-with-us/ip-commercialisation/Marketplace/Printed-solar-film>, 12 March 2023.

[78] Ibid., also see the Charge Around Australia initiative to use printed solar technology for off-grid electric car charging, <https://chargearoundaustralia.com/technology>, and <https://chargearoundaustralia.com/what-are-printed-solar-cell-panels>.

[79] Australian Research Council, 'Solar paint offers endless energy from water vapour', <https://www.arc.gov.au/news-publications/media/research-highlights/solar-paint-offers-endless-energy-water-vapour>.

[80] Zyga, L., 'Researchers prepare cheap quantum dot solar paint', December 2011, <https://phys.org/news/2011-12-cheap-quantum-dot-solar.html>, accessed 08 March 2023.

[81] Muhammad, A. A., 'Revival of Solar Paint Concept: Air-Processable Solar Paints for the Fabrication of Quantum Dot-Sensitized Solar Cells', *The Journal of Physical Chemical*, vol. 121, no. 33, 2017, p. 17658–17670, doi: 10.1021/acs.jpcc.7b05207.

[82] Gautum, A., 'Solar paint: the next big thing in renewable energy?', *Solar Review*, Jan 2023, <www.solarreviews.com/blog/solar-paint-hydrogen-quantum-dot-perovskite-solar-cells>, accessed 09 March 2023.

[83] Gharahcheshmeh, M. H., et. al., 'Tuning, Optimization, and Perovskite Solar Cell Device Integration of Ultrathin Poly (3,4-Ethylene Dioxythiophene) Films Via a Single-Step All-Dry Process', *Science Advances*, vol. 5, no. 11, 2019., doi:10.1126/sciadv.aay0414.

[84] Casey, T., 'Transparent Solar Window - You ain't seen nothing yet', *GreenTechnica*, November 2021, <https://cleantechnica.com/2021/11/27/transparent-solar-windows-you-aint-seen-nothing-yet>, accessed 12 March 2023.

[85] 'Greening the Future - Solar Glass', Edith Cowan University, <www.ecu.edu.au/research/worldclass/solarglass>, accessed 12 March 2023.

[86] Ibid.

[87] Barron-Gafford, G.A., *et al.*, 'Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands', *Nat Sustain,* 2019, vol. 2, pp. 848–855, doi: 10.1038/s41893-019-0364-5. See also, Abidin, M.A.Z., Mahyuddin, M.N., and Zainuri, M.A.A.M. (2022). 'Agrivoltaic Systems: An Innovative Approach to Combine Agricultural Production and Solar Photovoltaic System', in Mahyuddin, N.M., Mat Noor, N.R., Mat Sakim, H.A.

(eds) *Proceedings of the 11th International Conference on Robotics, Vision, Signal Processing and Power Applications*, vol 829, Springer, Singapore. doi: 10.1007/978-981-16-8129-5_119.

[88] Fischer, A., 'Agrivoltaics can provide food, energy for growing world population', *PV Magazine*, <www.pv-magazine-australia.com/2023/03/07/agrivoltaics-can-provide-food-energy-for-growing-world-population>, March 2023, accessed 27 April 2023.

[89] Until recently, most agrivoltaic-based efforts used opaque solar panels over and around agricultural spaces. The tradeoff has been between whether allowing light for the plants or optimizing for solar electricity generation. and Pascaris, A.S., Schelly, C., and Pearce, J.M., 'A First Investigation of agriculture sector perspectives on the opportunities and barriers for agrivoltaics', *Agronomy*, 2020, vol. 10, no.12, doi: 10.3390/agronomy10121885.

[90] ClearVuePV, R&D Greenhouse <www.clearvuepv.com/project/murdoch-university-greenhouse>, accessed 26 April 2023.

[91] Deboutte, G., 'Transparent solar panels for agrivoltaics', *pv magazine,* July 2, 2021, < https://www.pv-magazine.com/2021/07/02/transparent-solar-panels-for-agrivoltaics>, accessed 25 Sep 2023. See also, Stallknecht, E.J., *et al.* Designing plant–transparent agrivoltaics. *Scientific Rep*ort **13**, 1903 (2023). https://doi.org/10.1038/s41598-023-28484-5.

[92] Ibid.

[93] Huang, C-S., et al., 'Energy harvesting textiles: Using wearable luminescent solar concentrators to improve the efficiency of fiber solar cells', *Journal of Materials Chemistry* A, vol. 9, 2021, doi: 10.1039/D1TA04984D.

[94] Satharasinghe, A., T. Hughes-Riley, and T. Dias, 'A Review of Solar Energy Harvesting Electronic Textiles', *Sensors*, vol. 20, 5938, 2020, doi: 10.3390/s20205938.

[95] Puiu, T., 'Solar cells woven into fabric could turn any tent, curtain or clothes into a solar panel, XME Science, September 2016, <www.zmescience.com/science/news-science/solar-cell-fabric>, accessed 03 March 2023.

[96] Komolafe, A., 'E-Textile Technology Review - From Materials to Application', *IEEE Access*, pp. 97152 - 97179, 2021, doi: 10.1109/ACCESS.2021.3094303.

[97] Solar skin, <https://solarskin.com.au>, accessed 14 March 2023.

[98] Escobedo, P., et al., 'Energy Generating Electronic Skin with Intrinsic Tactile Sensing Without Touch Sensors', *IEEE Transactions on Robotics*, vol. 37, 2020, pp. 683-690.

[99] Ibid.

[100] 'Solar-powered synthetic skin could return touch to amputees', Springwise, <www.springwise.com/solar-powered-synthetic-skin-return-touch-amputees>, accessed 14 March 2023.

[101] Wang, K. et al., *Thermal Energy Storage for Solar Energy Utilization: Fundamentals and Applications*, 2020, doi: 10.5772/intechopen.91804.

[102] World Energy Council, *Five Steps to Energy Storage: Innovation Insights Brief*, London, U.K., 2020, p.43.

[103] International Renewable Energy Agency, *Innovation Outlook: Thermal Energy Storage*, IRENA, Abu Dhabi, 2020.

[104] Kalaiselvam, S., and R. Parameshwaran, 'Thermal Energy Storage Technologies', in Thermal Energy Storage Technologies for Sustainability, S. Kalaiselvam and R. Parameshwaran, eds., Academic Press, 2014, pp. 57-64, doi: 10.1016/B978-0-12-417291-3.00003-7.

[105] Ibid.

[106] Ibid.

[107] Ibid.

[108] Kisi, E., et al., 'Miscibility Gap Alloys: A New Thermal Energy Storage Solution', In Sayigh, A., eds., *Transition Towards 100% Renewable Energy. Innovative Renewable Energy*, Springer, Cham., 2018, doi: 10.1007/978-3-319-69844-1_48.

[109] It took over ten years of R&D to create a testable pilot of the MGA block and the MGA Thermal Energy Storage at the University of Newcastle.

[110] Australian Renewable Energy Agency, 'MGA Thermal to demonstrate a fresh approach to energy storage', <https://arena.gov.au/news/mga-thermal-to-demonstrate-a-fresh-approach-to-energy-storage>, accessed 02 March 2023.

[111] Sugo, H., Kisi, E. and Cuskelly, D. 'Miscibility gap alloys with inverse microstructures and high thermal conductivity for high energy density thermal storage applications', Applied Thermal Engineering, vol. 51, 2013, pp. 1345-1350.

[112] Ibid.

[113] Australian Renewable Energy Agency, ' Thermal energy: Can MGA fill a battery gap?' August 2022, < https://arena.gov.au/blog/thermal-energy-can-mga-fill-a-battery-gap>, accessed 02 March 2023.

[114] Ibid.

[115] The University of Newcastle Australia, 'The missing block to build an all-renewable electric grid', <https://www.newcastle.edu.au/newsroom/featured/the-missing-block-to-build-an-all-renewable-electric-grid>, accessed 02 March 2023.

[116] Ibid.

[117] MGA Thermal < https://www.mgathermal.com>, accessed 02 March 2023.

[118] Australian Renewable Energy Agency, 'MGA Thermal to demonstrate a fresh approach to energy storage', <https://arena.gov.au/news/mga-thermal-to-demonstrate-a-fresh-approach-to-energy-storage>, accessed 02 March 2023.

[119] Ibid.

[120] MGA Thermal < https://www.mgathermal.com>, accessed 02 March 2023.

[121] For more information about the project see: <https://arena.gov.au/projects/mga-thermal-energy-storage-project>, <https://arena.gov.au/news/mga-thermal-to-demonstrate-a-fresh-approach-to-energy-storage>, and <www.mgathermal.com/pilot>.

[122] Australian Renewable Energy Agency, 'AGL Thermal Storage at Torrens Island Power Station B Feasibility Study', February 2023, <https://arena.gov.au/projects/agl-thermal-storage-at-torrens-island-power-station-b-feasibility-study>, accessed 14 March 2023. For more information about the project see: <https://arena.gov.au/news/repurposing-power-stations-for-renewable-thermal-energy-storage-solutions> and < https://arena.gov.au/blog/renewable-storage-heating-up-at-torrens-island>.

[123] United Nations SDG1: No poverty, <https://sdgs.un.org/goals/goal1>, accessed 08 April 2023.

[124] United Nations SDG3: Good health and well-being, <https://sdgs.un.org/goals/goal3>, accessed 08 April 2023.

[125] United Nations SDG4: Quality education, <https://sdgs.un.org/goals/goal4>, accessed 08 April 2023.

[126] United Nations SDG5: Gender equality, <https://sdgs.un.org/goals/goal5>, accessed 08 April 2023.

[127] United Nations SDG13: Climate action, <https://sdgs.un.org/goals/goal13>, accessed 08 April 2023.

[128] United Nations SDG7: Affordable and clean energy, <https://sdgs.un.org/goals/goal7>, accessed 08 April 2023.

[129] United Nations SDG8: Decent work and economic growth, <https://sdgs.un.org/goals/goal8>, accessed 08 April 2023.

[130] United Nations SDG13: Climate action, <https://sdgs.un.org/goals/goal13>, accessed 08 April 2023.

[131] International Renewable Energy Agency, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, IRENA, Abu Dhabi, 2019.

[132] International Renewable Energy Agency and International Labour Organization, *Renewable energy and jobs: Annual review 2022*, IRENA, Abu Dhabi and ILO, Geneva, 2022.

[133] Ibid.

[134] Ibid.

[135] International Labour Organization, Green Jobs for Youth Pact - Accelerating young talent and skills for green jobs, < www.climateaction4jobs.org/youth>, accessed 12 March 2023.

[136] Popescu, V.D., *et al.* Quantifying biodiversity trade-offs in the face of widespread renewable and unconventional energy development. *Scientific Reports,* vol. 10, 7603, 2020, doi: 10.1038/s41598-020-64501-7. Sonter, L.J., *et al.*, 'Renewable energy production will exacerbate mining threats to biodiversity', *Nature Communications,* vol. 11, 4174, 2020, doi: 10.1038/s41467-020-17928-5.

[137] Daewel, U., *et al.* 'Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea', *Communications Earth & Environ*ment, vol.3, 292, 2022, doi:10.1038/s43247-022-00625-0.

[138] International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report*, IEA, Paris, 2021. For an exposé of the massive toll of cobalt mining on the people and

environment of the Democratic Republic of the Congo as told through the testimonies of the Congolese people, see Kara, S., *Cobalt Red: How the Blood of the Congo Powers Our Lives*, St. Martin's Press, London, 2023.

[139] Business and Human Rights Resource Centre, *Transition Mineral Tracker*, <www.business-humanrights.org/en/from-us/transition-minerals-tracker>, accessed 18 March 2023. See also from Business and Human Rights Resource Centre, *Renewable Energy and Human Rights Benchmark*, 2020 <www.business-humanrights.org/en/from-us/briefings/renewable-energy-human-rights-benchmark>; *Human Rights in the Mineral Supply Chains of Solar Panels*, 2019, <www.business-humanrights.org/en/from-us/briefings/transition-minerals-sector-case-studies/human-rights-in-the-mineral-supply-chains-of-solar-panels>.

[140] Business and Human Rights Resource Centre, *Transition Mineral Tracker: 2021 Global analysis of human rights in the energy transition*, May 2022, <www.business-humanrights.org/en/from-us/briefings/tmt-2021>, accessed 18 March 2023.

[141] Ibid.

[142] IRENA and IEA-PVPS, *End-of-Life Management: Solar Photovoltaic Panels*, International Renewable Energy Agency and International Energy Agency-Photovoltaic Power Systems, 2016.

[143] Atasu, A., Duran, S., and Van Wassenhove, L. N., 'The Dark Side of Solar Power', *Harvard Business Review*, June 2021, <https://hbr.org/2021/06/the-dark-side-of-solar-power>, accessed 18 March 2023.

[144] Ibid.

[145] The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Mining biotechnology, <www.csiro.au/en/work-with-us/industries/mining-resources/Mining/Mining-biotechnology>, accessed 26 April 2023.

[146] National Renewable Energy Laboratory, *Circular Economy for Photovoltaics Factsheet,* NREL, Golden, Co, October 2021.

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